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The present volume contains the contributions from the Woods Hole Oceanographic Institution which appeared during 1944, 1945 and 1946, in publications other than *Papers in Physical Oceanography and Meteorology;* also the Annual Report of the Director for the years 1943, 1944 and 1945.

TABLE OF CONTENTS

Contribution
No.

301. F. G. WALTON SMITH
Effect of Water Currents upon the Attachment and Growth of Barnacles.

329. A. A. ABRAMOWITZ, F. L. HISAW and D. N. PAPANDREA
The Occurrence of a Diabetogenic Factor in the Eyestalks of Crustaceans.

330. RICHARD E. LEE
A Quantitative Survey of the Invertebrate Bottom Fauna in Menemsha Bight.

331. ALFRED H. WOODCOCK
A Theory of Surface Water Motion Deduced from the Wind-Induced Motion of the Physalia.

332. LOUIS W. HUTCHINS
An Annotated Check-List of the Salt-Water Bryozoa of Long Island Sound.

333. HENRY B. BIGELOW and WILLIAM C. SCHROEDER
New Sharks from the Western North Atlantic.

334. W. J. CLENCH and C. G. AGUAYO
A New Tropical Buccinum from Cuba.

335. BOSTWICK H. KETCHUM, JOHN D. FERRY and ALFRED C. REDFIELD
Evaluation of Anti-fouling Paints by Leaching Rate Determinations.

336. GEORGE T. SCOTT
The Influence of H-ion Concentration on the Mineral Composition of *Chlorella pyrenoidosa*.

337. GEORGE T. SCOTT
The Mineral Composition of Phosphate Deficient Cells of *Chlorella pyrenoidosa* during the Restoration of Phosphate.

338. FRED B PHLEGER, JR.
Vertical Distribution of Pelagic Foraminifera.

339. WARREN H. YUDKIN
Occurrence of Thiaminase in Marine Teleosts.

341. NELSON MARSHALL
Observations on the Comparative Ecology and Life History of two Sea Robins, *Prionotus carolinus* and *Prionotus evolans strigatus*.

342. JOHN D. FERRY and DAYTON E. CARRITT
Action of Antifouling Paints. I. Solubility and Rate of Solution of Cuprous Oxide in Sea Water.

343. M. JUUL HVORSLEV and HENRY C. STETSON
Free-Fall Coring Tube: A New Type of Gravity Bottom Sampler.

Contribution
No.

344. FRED B PHLEGER, JR. and WALTER A. HAMILTON
Foraminifera of Two Submarine Cores from the North Altantic Basin.

345. JOHN D. FERRY and GORDON A. RILEY
Action of Antifouling Paints. II. Solubilities of Antifouling Toxics in Sea Water.

346. JOHN D. FERRY and BOSTWICK H. KETCHUM
Action of Antifouling Paints. III. Maintenance of the Leaching Rate of Antifouling Paints Formulated with Insoluble, Impermeable Matrices.

347. BOSTWICK H. KETCHUM, JOHN D. FERRY and ARTHUR E. BURNS, JR.
Action of Antifouling Paints. IV. Maintenance of Leaching Rate of Antifouling Paints Formulated with Soluble Matrices.

348. MAURICE EWING, ALLYN VINE and J. L. WORZEL
Photography of the Ocean Bottom.

349. C. M. POMERAT and C. M. WEISS
The Influence of Texture and Composition of Surface on the Attachment of Sedentary Marine Organisms.

350. MARSHALL SCHALK
A study of Textural Changes in a Beach by Repeated Samplings.

351. MAURICE EWING, G. P. WOOLLARD, A. C. VINE and J. L. WORZEL
Recent Results in Submarine Geophysics.

352. GORDON A. RILEY and DEAN F. BUMPUS
Phytoplankton-Zooplankton Relationships on Georges Bank.

353. GORDON A. RILEY
Factors Controlling Phytoplankton Populations on Georges Bank.

354. H. R. SEIWELL
Military Oceanography in Tactical Operations of World War II.

363. GEORGE L. CLARK
Dynamics of Production in a Marine Area.

THE WOODS HOLE OCEANOGRAPHIC INSTITUTION
Report for the years 1943, 1944 and 1945.

LIST OF CONTRIBUTIONS

Contribution No. 301

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EFFECT OF WATER CURRENTS UPON THE ATTACHMENT AND GROWTH OF BARNACLES[1]

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Introduction

There exists a considerable body of published work dealing with peculiarities in the distribution of sessile marine invertebrates in general, and, although experimental evidence is incomplete some speculation has been offered as to the manner in which their distribution is limited by various factors of the environment which influence their attachment and growth. The object of the present studies was to investigate the action of the water current factor by experimental methods, with particular reference to the species of barnacles which are most abundant in the Miami area.

Much of the earlier work on sessile marine animals has been reviewed by Mc Dougall (1943), and need not be considered here in detail. A bibliography of investigations dealing with sessile organisms from the point of view of ship fouling is given by Neu (1933), and an excellent general account of marine fouling by Visscher (1928) who does not, however, include more than a brief reference to the effect of water currents.

The effects of environmental factors have been deduced from the results of ecological surveys by a number of investigators. Stephenson and his co-workers, in a series of publications entitled *The South African Zone and Its Relation to Water Currents* (see bibliography), Fischer-Piette (1928, 1928a), Pierron and Huang (1926), and Prennant and Teissier (1924) have described the populations of rocky shores and the distribution of sessile organisms in general, but with scanty reference only to the relation between barnacle attachment and the velocity of water currents. Stephenson and Bright (1938) and Stephenson and du Toit (1937), however, note the absence of certain species of barnacles from surfaces exposed to heavy wave action.

The possibility of water movement influencing barnacle attachment is suggested by Fischer-Piette (1932) in his reports on surveys of the shores of the English Channel. Shelford and Towler (1925), Towler (1930), and Newcombe (1935) have paid particular attention to barnacles in associations of Balanus-Littorina and Balanus-Mytilus and draw attention to the more luxuriant growth of barnacles exposed to strong water currents, particularly in shallow water. The role of water currents is also mentioned briefly in accounts of ecological surveys by Rice (1930), Moore (1935a), and Moore and Kitching (1939), who stress the part played by them in the provision of an adequate food supply, as well as the adverse effects of wave action.

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[1] These experiments were conducted while the author was engaged by the Woods Hole Oceanographic Institution in investigations under contract with the Bureau of Ships, Navy Department, which has given permission to publish the results. The opinions contained herein are those of the author and do not necessarily reflect the official opinion of the Navy Department or of the Naval service at large.

[2] Contribution number 301 from the Woods Hole Oceanographic Institution.

Experimental investigation has yielded more direct information. Moore (1933) studied the effect of currents upon the attachment of cyprid larvae with particular regard to orientation, but gives no estimate of current velocities which limit attachment. The related phenomena of wave action are considered by Moore in a separate paper (1939).

Evidence as to the effect of water currents is also afforded by the study of ships and other objects moving through the water. The economic importance of ship-bottom fouling has stimulated this kind of observation. Heutschel (1934) and Neu (1932) state that vessels collect barnacles most readily when in harbor and when subjected to relatively less water movement. Visscher (1930) further observes that barnacles are usually killed during ocean passages of about 500 miles. Hiraga (1934) showed experimentally that, in the laboratory, 10 to 17 day old barnacles were lost during a five day exposure of test planks to water currents, whereas twenty-four day old barnacles remained alive and intact. In a later paper of Visscher (1938) he concludes that barnacles are not distributed by ships. This is contrary to the views of Fischer-Piette (1929, 1935) who expresses the opinion that *Balanus amphitrite* found by him on the coast of France, was brought from the tropics on the hulls on ships. Later observations by Phelps (1942) on test panels support the conclusion that excessive water currents inhibit the attachment and growth of barnacles.

The extensive observations of McDougall on the pile fauna at Beaufort include the results of exposing various types of experimental collecting apparatus. His experiments on the effect of water currents indicate that fewer barnacles settle and that growth is slower in more rapid currents. His results did not, however, give an accurate indication of limiting or optimum velocities to which his collectors were exposed.

The experiments which form the subject of the present account are divided into a study of the effects of water currents upon the attachment of cyprid larvae, and into a consideration of the effects of water currents upon the organisms following attachment. Under natural conditions of fluctuating tidal currents and wind drifts it is conceivable that a cyprid might attach during a period of minimum water flow in a particular region and that, once attached, the maximum flow would be insufficient to detach it or to inhibit its growth. The aim of the investigation was to establish the limiting velocities of current for initial and continued attachment and growth.

The advice and suggestions of Dr. Alfred C. Redfield of the Woods Hole Oceanographic Institution are gratefully acknowledged. The writer is also indebted to Mr. Frank L. LaQue of the Development and Research Division, International Nickel Company, Inc. and to Dr. William F. Clapp for permission to include in this paper data from their observations at Kure Beach, N. C. Acknowledgments are also due Mr. D. S. Reynolds, Mr. James Gregg, Mr. Alexander Frue, and Mr. Charles Weiss for their assistance at various times.

METHODS

In order to study the effects of water currents two types of apparatus were designed which would permit the movement of sea-water relative to the experimental surface at predetermined and variable velocities. The first consisted of a rotating disc, immersed in the sea. The second type of apparatus consisted of a series of glass tubes of varying cross-sectional diameter. The rotating disc was employed both in the study of initial attachment of barnacles and in the study of growth subsequent to attachment. The glass tubes of graded diameter were employed in the observations on initial attachment only, as a check against results obtained with the rotating disc.

Water Currents and Attachment on the Rotating Disc

The rotating disc apparatus as used in the experiments here described is essentially similar to a machine described by LaQue (1943) for the purpose of studying the effect of sea-water currents upon corrosion of metal samples, with certain changes in design appropriate to the particular use to which it was put. The modified machine consists of a vertical shaft rotated by means of an electric motor and a system of belts and pulleys. The disc is attached to the shaft by means of a flange and small brass screws and is maintained in a position several inches below low water spring tide. At velocities of rotation used in the experiment no cavitation occurred at this depth.

By changing the arrangement of pulleys the speed of rotation may be varied up to approximately 1750 r.p.m. The rate of movement in knots of any portion of the disc relative to an imaginary stationary body of water is readily calculated as approximately $R \times D/370$, where R is the number of revolutions per minute and D the diameter in inches. This velocity is nominal, however, and does not accurately represent the rate of relative movement between the disc and the water close to its surface. Frictional drag and centrifugal forces produce vortex movements which cause water to flow in a close spiral roughly parallel to the plane of the disc. As a result, the actual flow of water at any part of the disc's surface is less than the nominal rate calculated from the velocity of rotation. Size of the discs used varied up to 28 inches in diameter.

Experimental procedure consisted of bolting a new rotating disc on the shaft and setting the machinery in continuous operation. The disc was removed and examined at suitable intervals. At the same time a similar stationary disc was immersed at a point nearby the rotating disc, at the same depth and resting similarly in a horizontal plane. Observations on the second disc acted as a control for such factors as abundance of organisms, nature of the surface of the disc, etc. The apparatus was used at the edge of a covered slip at the Miami Beach Boat Corporation, where fouling is usually severe. The predominant organism at most times of the year is *Balanus amphitrite niveus* Darwin and this was accordingly selected for observation.

Results

The results of the first rotating disc experiment indicated that the approximate minimum current velocity required to prevent barnacle attachment is 1.1 knots. The disc used was 13 inches in diameter and was rotated at 540 r.p.m. The disc, together with its stationary control, are shown in Figure 1 as they appeared at the end of this experiment. Five barnacles attached to the center of the rotated disc during 23 days but did not grow beyond 2 mm. in greatest width. The limiting velocity was calculated from the ¾ inch diameter of the circle to which the barnacle attachments were restricted (Table I).

TABLE I

Effect of water currents upon attachment of Balanus amphitrite as observed on the lower surface of a horizontal rotating disc

Disc	Date of start	Duration of rotation (Days)	Speed of rotation (r.p.m.)	Maximum diameter at which attachment occurred (Inches)	Maximum nominal velocity at which attachment occurred (Knots)
1 B	8/20/43	23	540	¾	1.1
4 A	11/4/43	16	192	2	1.0
6 A	12/7/43	14	134	2½	0.9
7 A	1/5/44	19	60	8	1.3
Average	—	—	—	—	1.1

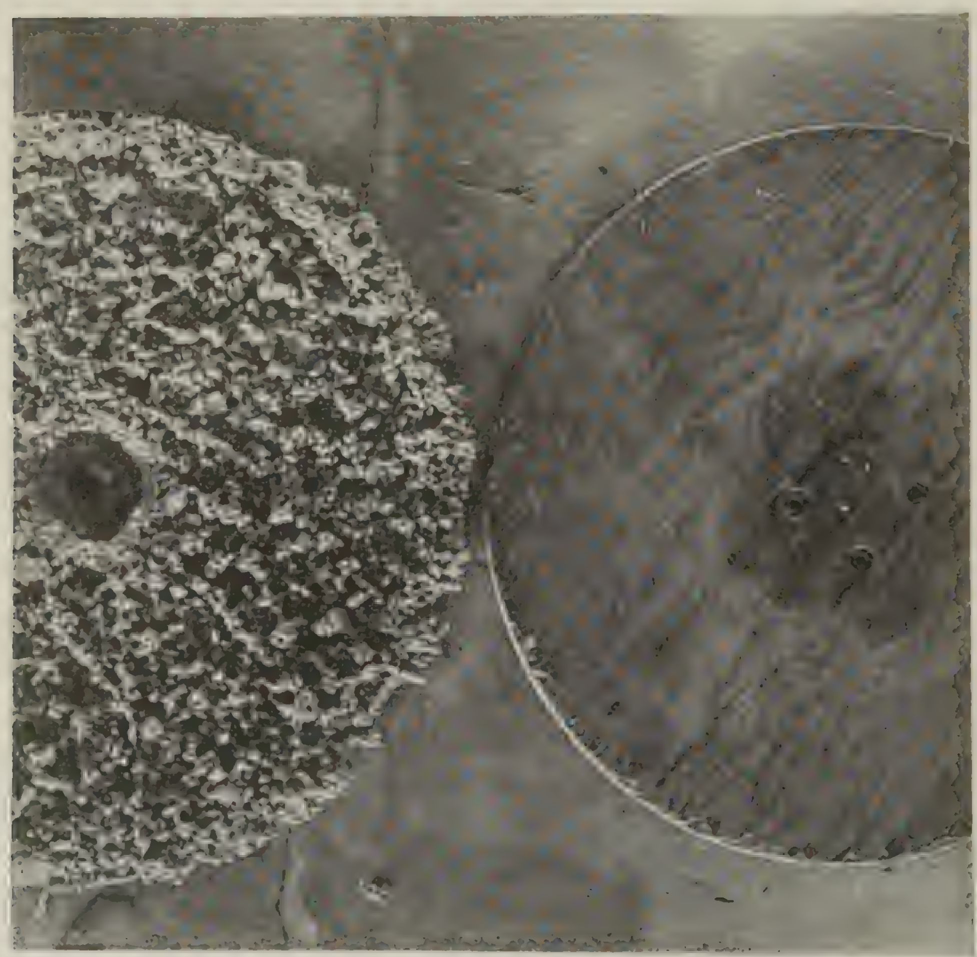

FIGURE 1. Surface of disc rotated at 540 r.p.m. for a period of 23 days, together with stationary control. Diameter of disc, 13 inches.

In order to establish the limiting velocity with greater accuracy the experiment was repeated on three other occasions at slower speeds of rotation, with the results shown in Table I and Figure 2. The nominal velocity limiting barnacle attachment as shown by these experiments varied from 0.9 knots to 1.3 knots with an average of 1.1 knots. In addition to the adverse effect upon barnacle attachment it was noticed that slime film development was greatly reduced on the rotated disc.

ATTACHMENT IN GLASS TUBES

Owing to the difficulty of accurately measuring the rate of water flow along the surface of the rotating disc, an independent method of investigating the relation between water currents and fouling incidence was used. In this case sea water was passed through sections of glass tubing of varying diameter (Fig. 3). Comparison of fouling incidence in each sector was made with the varying linear velocity of the water, calculated on the assumption that linear rate of flow through tubes varies inversely as the square of the diameter of cross-section. In order to estimate errors which might be introduced by virtue of turbulent flow, carmine was introduced into the water during a preliminary test run. It was observed that flow in the main portion of each section was smooth. Areas near to the joints, where turbulence was noted, were not included in the experimental observations of fouling incidence.

The tubes were approximately eight inches long and of 5 cm., 3.7 cm., 2.8 cm., 2.2. cm., and 1.4 cm. internal diameter respectively and were joined by means of fitted rubber stoppers. Attachment of barnacle larvae was encouraged by excluding direct sunlight. The water flow was provided by means of a centrifugal pump, with the experimental tubes arranged on the inlet side in order to avoid possible mechanical damage to the larvae.

While the apparatus was in operation the rate of flow was checked daily by volumetric measurement at the outlet. At the conclusion of each test run the tubes were carefully examined for signs of fouling.

Results

Observations on the glass tubes showed that limiting velocities for attachment of *Balanus amphitrite* were between 0.5 and 1.0 knot. During the first experiment with this apparatus, sea water was run through it at a rate between 13 and 16 liters per minute, on a catwalk extending over the water at the University of Miami Marine Laboratory. Fluctuations in the height of tide and consequently the suction head of the seawater pump gave rise to this fluctuation in current velocity. Barnacles attached in the two larger tubes within ten days after beginning the experiment. From the calculated linear velocity of the narrower of these tubes it appeared that barnacles are not prevented from attachment by currents varying between 0.5 and 0.6 knot (Table II). In the next smaller tube where no barnacles attached the rate of flow varied from 0.8 to 1.0 knot. The limiting velocity therefore lies between 0.5 knot and 1.0 knot. The appearance of the tubes at the end of a similar experiment is illustrated in Figures 3 and 4. The upper figure of the limits is lower than the critical velocity as measured on the rotating disc. However, in view of the difference in hydrodynamical conditions involved in the two methods, which was discussed previously, the results appear to be reasonably consistent.

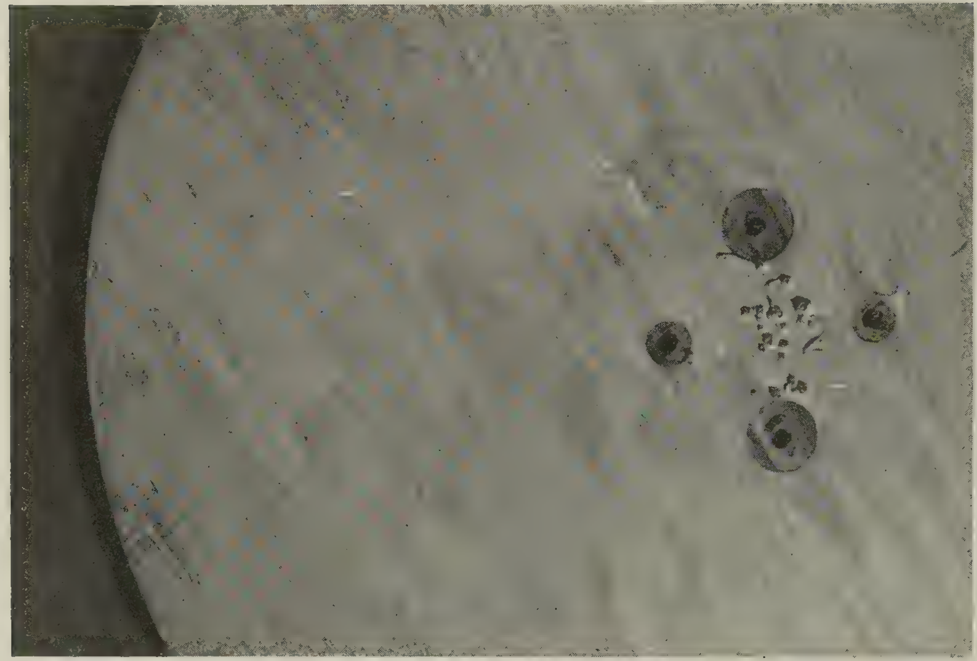

Figure 2. Portion of disc rotated at 192 r.p.m. for a period of 16 days, showing barnacles attached at center. Diameter of disc, 24 inches.

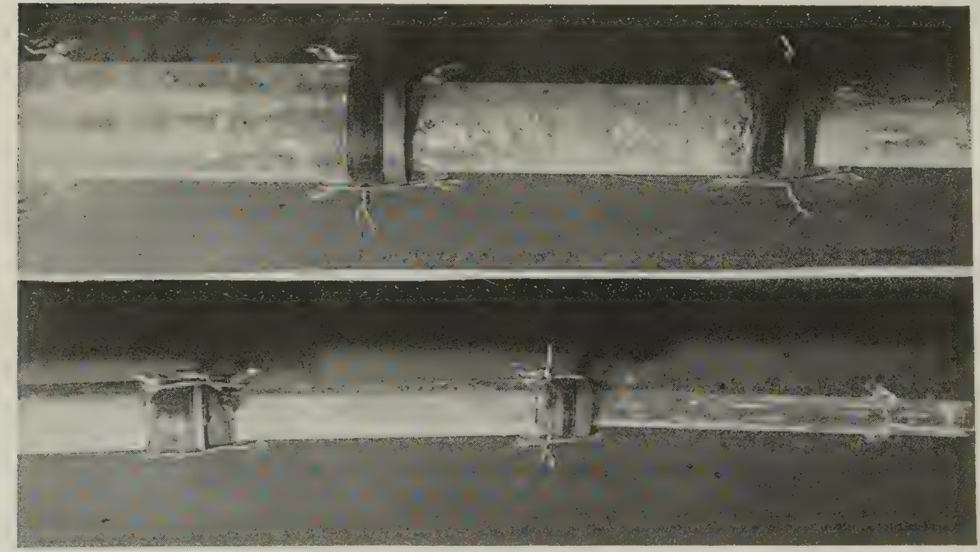

Figure 3. Series of five tubes of increasing cross-sectional diameter. Shows development of barnacles in wider tubes only, following prolonged passage of sea-water.

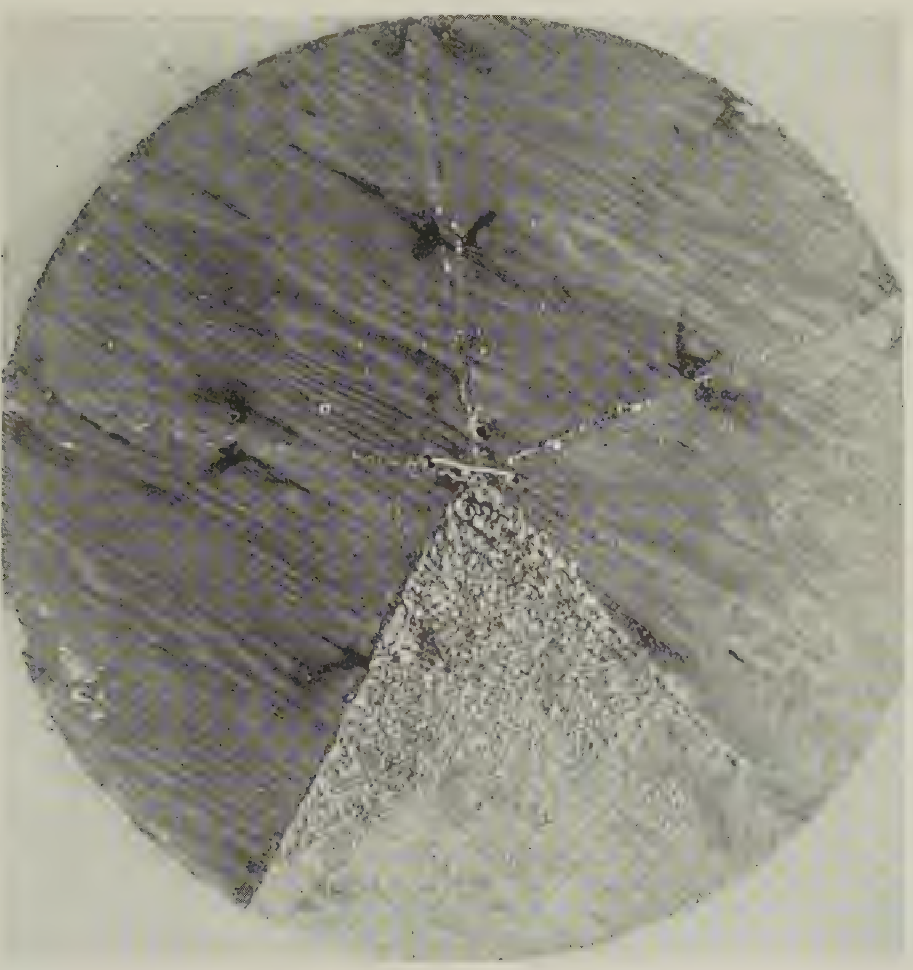

FIGURE 4. Surface of disc following 16 days of stationary immersion beginning January 8, 1944. Individual sectors of the disc were exposed for periods of 6 hrs., 1 day, 2 days, 5 days and 16 days. Diameter of disc, 28 inches.

At a later date the glass tubes were exposed at Kure Beach, N. C., by Mr. F. L. LaQue and Dr. W. Clapp, under conditions allowing a more constant flow of sea water. By reducing the flow of water in successive experiments the critical velocity for attachment was confined more closely between 1.1 and 1.3 knots for *Balanus improvisus* and below 0.8 knot for *B. eburneus*. These results are included in Table II with the permission of LaQue and Clapp.

Confirmatory results have been reported by Turner (1945) from an experiment recently conducted at Kure Beach in which a system of steel pipes of graded diameter was exposed to sea water circulation for 98 days. Fouling with mussels, barnacles, and tube worms occurred where the current velocity was one knot or less but not where it was 1.8 knots or greater.

TABLE II

Attachment of Balanus species upon vertical glass tubes of graded diameter during the passage of sea-water

Period and place	Rate of flow. Liters per minute	Equivalent velocity in glass tubes (Knots)				
		1.4 cm. diameter	2.2 cm. diameter	2.8 cm. diameter	3.7 cm. diameter	5.0 cm. diameter
11/17/43 to 11/27/43 Miami Beach	13–16	3.0–3.7 —	1.2–1.6 —	0.8–1.0 —	0.5–0.6 *B. amphitrite*	0.2–0.3 *B. amphitrite*
5/20/44 to 7/12/44 Kure Beach*	21	5.3 —	2.3 —	1.4 —	0.8 Balanus sp.	0.4 Balanus sp.
7/12/44 to 9/18/44 Kure Beach*	12.7	3.2 —	1.3 —	0.8 Balanus sp.	0.5 Balanus sp.	0.2 Balanus sp.
9/18/44 to 11/25/44 Kure Beach*	10.8	2.7 —	1.1 *B. improvisus*	0.7 *B. improvisus*	0.4 *B. eburneus* *B. improvisus*	0.2 *B. eburneus* *B. improvisus*

* Observations by W. F. Clapp and F. L. LaQue.

GROWTH ON THE ROTATING DISC

For the purpose of studying the effect of water currents upon barnacles already attached the rotating disc procedure was modified. Both rotating and stationary discs were allowed a preliminary period of stationary immersion during which barnacles became attached. Equal sectors of the disc were temporarily protected by means of cloth attached with thumb tacks. The cloth was removed from each sector after increasing intervals of time with the result that at the end of the preliminary period of immersion the maximum age of the organisms attached to the different parts of the disc varied from 16 days to 6 hours. The barnacles on each sector were then counted and the maximum diameter of the largest barnacle in each sector was measured.

Following the period of stationary immersion the control disc was allowed to remain in a stationary position and the other was placed on the rotating shaft for a further period. Both discs were examined and the number of barnacles per square inch and their greatest diameter were recorded separately for each sector and for areas at successive distances from the center of the disc.

Results

The first experiment of this series provided an initial 16 days' period of stationary immersion during which both experimental and control discs became seeded with barnacles. At the end of this period barnacles had been attached on the five sectors for maximum periods of 6 hours, 1 day, 2 days, 5 days, and 16 days respectively (Fig. 4). Immediately following the period of stationary growth, the experimental disc was rotated at an angular velocity of 60 r.p.m. for 19 consecutive days, while the control disc was allowed to remain in a stationary position for the same period. The appearance of both discs at the end of the experiment is shown in Figures 5 and 6.

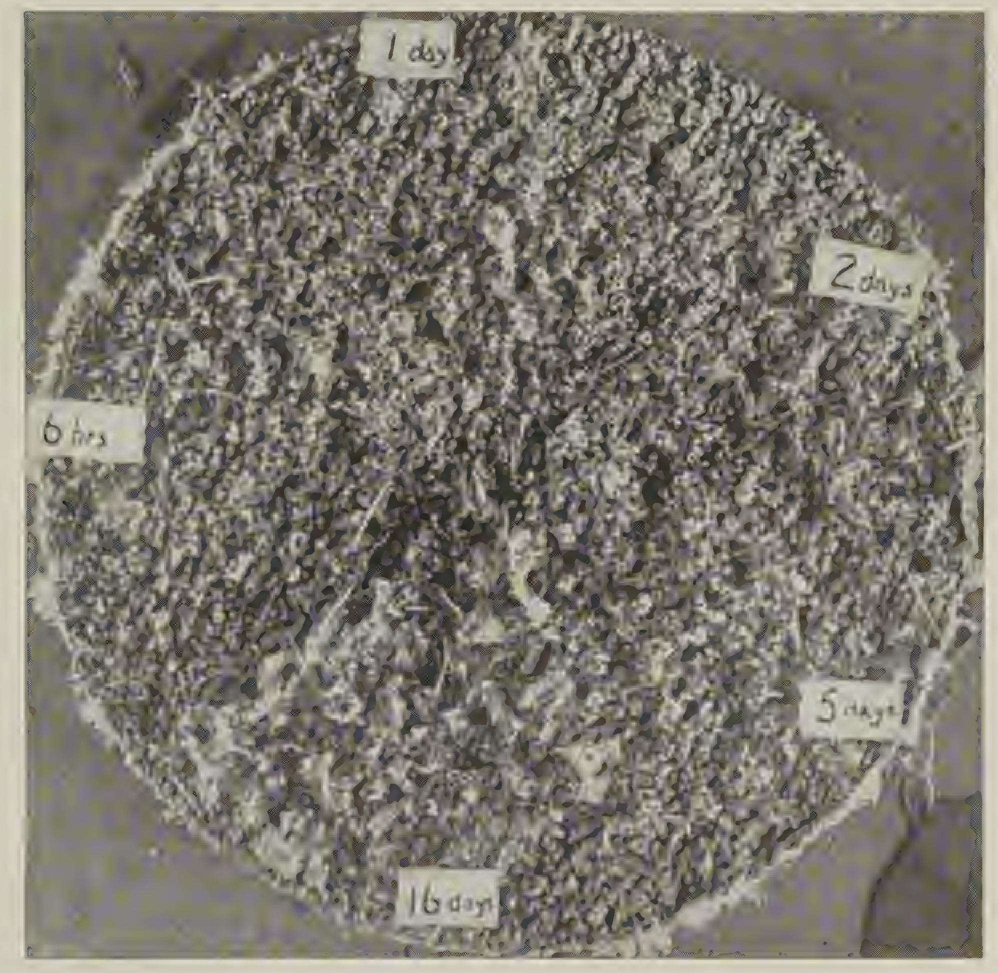

FIGURE 5. Same disc as in Figure 4 after further period of 19 days stationary immersion. Control to disc shown in Figure 6.

Examination of the discs at the conclusion of the test showed that while increasing current velocities diminished the growth rate and finally brought about loss of attachment, the weaker currents appeared to enhance growth. Thus, when rotated on Sector I, where growth had continued for 6 hours before rotation, *B. amphitrite*

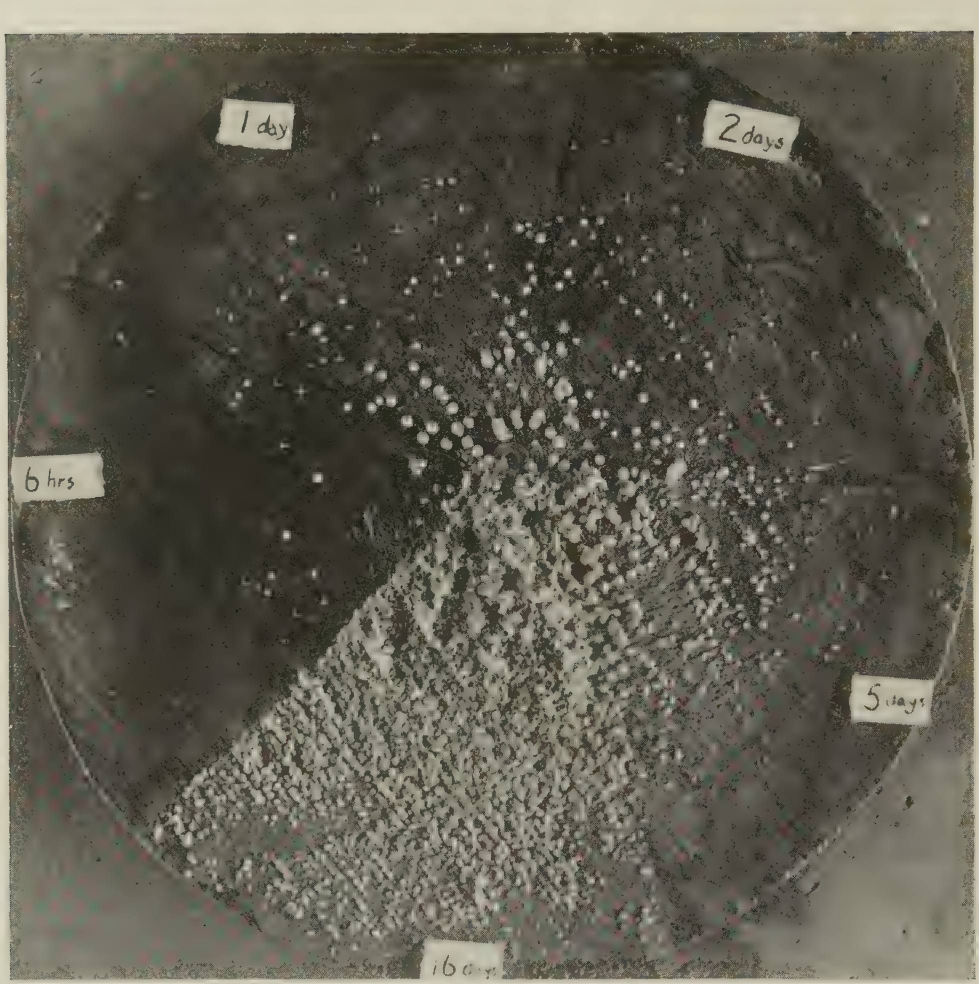

FIGURE 6. Similar disc to that of Figure 4 after period of 19 days rotation at 60 r.p.m. Age of barnacles before rotation is marked on each sector.

neither continued development nor remained attached at diameters beyond 16 inches, corresponding to a current of 2.7 knots (Table III). Within Sector VI, however, with barnacles originally 16 days old, a small number remained attached even at the outer edge of the disc, where the water flow approximated 4.7 knots. On the intervening sectors with barnacles of intermediate ages, the current velocities bringing about complete loss of attachment showed values between these extremes. Probably because of further attachments on the stationary control, the density of attachments on all sectors of the rotated disc was below that of the control.

The effects upon growth rate are illustrated by the observations in Table IV. On Sector I, within a 4 inch diameter, equivalent to 0.7 knot, barnacles reached a maximum width of 8 mm., compared with growth on the control of only 7 mm. At 2.3 knots, growth was reduced to only 3 mm. and at 2.7 knots, no barnacles re-

TABLE III

Effect of water currents upon adhesion of barnacles of different ages when subjected to 19 days rotation upon a submerged disc, as shown by density of attachment in number per square inch. Experiment initiated January 8, 1944

Position on disc		Age before rotation				
Diameter (Inches)	Nominal water velocity (Knots)	Sector I (6 hours)	Sector II (1 day)	Sector III (2 days)	Sector IV (5 days)	Sector V (16 days)
0–28*	0	Dense	Dense	Dense	Dense	Dense
4	0.7	1.7	1.7	1.7	2.0	Too crowded to count
6	1.0	0	0.4	0.9	1.7	
8	1.3	0	0.4	1.0	1.3	
10	1.7	0.1	0.4	1.0	1.0	
12	2.0	0.2	0.4	0.6	1.9	
14	2.3	0.1	0.4	0.9	1.3	
16	2.7	0	0.4	0.6	0.9	
18	3.0	0	0.1	0.2	0.6	
20	3.3	0	0	0.1	0.4	
22	4.0	0	0	0	0	
28	4.7	Few in cracks	0	Few in cracks	Few in cracks	Few

* Stationary control.

mained on the sector. At intermediate current velocities conditions of growth lay between these two extremes, with normal growth occurring between 0.7 and 1.7 knots.

Similar observations were made upon barnacles of greater initial age within the remaining sectors. Thus, on Sector IV, where development had continued for a maximum period of 5 days before rotation, barnacles showed enhanced growth rate in currents up to one knot, normal growth similar to that of the control up to 2 knots, and almost complete cessation of growth at 3.3 knots. No barnacles remained on this sector at 4 knots.

Similar conditions of enhanced growth at low velocities, normal growth at intermediate velocities and cessation of growth with loss of attachment at higher velocities were observed on the remaining sectors, with barnacles of different initial ages.

The anomalous absence of enhanced growth on Sector V is probably due to the crowded condition of the barnacles which had become attached during a 16 day stationary period. The one day old barnacles were apparently less affected by the

TABLE IV

Effect of water currents upon growth of barnacles of different ages when subjected to 19 days rotation upon a submerged disc, as shown by diameter of largest barnacle in millimeters. Experiment initiated January 8, 1944

Position on disc		Age and size before rotation				
Diameter (Inches)	Nominal water velocity (Knots)	Sector I 6 hours (<1 mm.)	Sector II 1 day (<1 mm.)	Sector III 2 days (<1 mm.)	Sector IV 5 days (2 mm.)	Sector V 16 days (5 mm.)
0–28*	0	7 mm.	7 mm.	8 mm.	8 mm.	9 mm.
4	0.7	8 mm.	8 mm.	8 mm.	9 mm.	None more than 8 mm.
6	1.0	—	8 mm.	9 mm.	9 mm.	
8	1.3	—	8 mm.	8 mm.	8 mm.	
10	1.7	6 mm.	7 mm.	6 mm.	8 mm.	
12	2.0	5 mm.	5 mm.	6 mm.	8 mm.	
14	2.3	3 mm.	6 mm.	4 mm.	6 mm.	
16	2.7	—	5 mm.	3 mm.	5 mm.	
18	3.0	—	1.5 mm.	1.5 mm.	4 mm.	7 mm.
20	3.3	—	—	1.5 mm.	2.5 mm.	6 mm.
24	4.0	—	—	—	—	6 mm.
28	4.7	1.5 mm.	—	1.5 mm.	4 mm.	5 mm.

* Stationary control.

inhibitory action of water currents than the two day old barnacles. Otherwise, the adverse effects of water currents increased with their velocity, and decreased with the initial age of the barnacles.

On all sectors a few barnacles continued to grow at the perimeter of the disc where the presence of cracks provided local flow pockets with relatively still water.

The first experiment demonstrated an actual loss of barnacles at current velocities having critical values for the different initial ages of barnacles. In order to determine the time required for the loss of attachment to occur, a second experiment was carried out in which the disc was examined, not only at the beginning and end of the rotation period, but also at intervening times. The density of attachment and maximum size of barnacles were observed at each examination, as in the previous experiment.

The experiment was carried out during a period of heavy barnacle set. At the end of the stationary period, extending from February 19 to March 1, 1945, the density of attachments upon each sector, and particularly upon the sectors longest exposed, was very much greater than in the previous experiment.

TABLE V

*Density of barnacle attachment compared with rate of flow of water relative to the surface of a rotating disc, expressed in number per square inch **
(Figures in brackets indicate density upon a stationary panel serving as control; D, over 75 per square inch)

Stationary growth period	Diameter of disc (Inches)	Velocity (Knots)	Period of rotation							
			0 hrs.	1 hr.	12 hrs.	3 days	5 days	7 days	9 days	11 days
Sector I	Control	(0)	(30)	(30)	(30)	(30)	(30)	(60)	(D)	(D)
	4	1.5	30	25	25	20	15	10	8	5
	8	3	30	30	20	20	15	10	8	6
6 hrs.	12	5	30	30	20	20	15	6	6	6
	16	6.5	30	30	20	20	15	6	6	5
	20	8	30	30	20	20	15	4	4	2
	24	10	35	30	20	20	12	4	4	2
Sector II	Control	(0)	(30)	(30)	(30)	(30)	(30)	(60)	(D)	(D)
	4	1.5	30	30	30	30	20	15	15	8
	8	3	30	30	30	30	20	15	15	12
12 hrs.	12	5	30	30	30	30	20	15	15	6
	16	1.5	30	30	30	30	20	15	15	6
	20	8	30	30	30	30	20	10	10	5
	24	10	30	30	30	10	7	7	7	4
Sector III	Control	(0)	(30)	(30)	(30)	(30)	(30)	(60)	(D)	(D)
	4	1.5	30	30	30	20	20	12	12	10
	8	3	30	30	30	20	20	12	12	12
1 day	12	5	30	30	30	20	12	10	10	10
	16	6.5	30	30	30	20	12	10	10	6
	20	8	30	30	30	20	12	7	7	5
	24	10	30	30	30	7	5	5	4	4
Sector IV	Control	(0)	(30)	(30)	(30)	(40)	(40)	(50)	(D)	(D)
	4	1.5	30	30	30	20	20	17	17	15
	8	3	30	30	30	24	20	20	20	19
2 days	12	5	30	30	30	24	20	20	15	9
	16	6.5	30	30	30	24	20	20	15	8
	20	8	30	30	30	15	10	10	10	7
	24	10	30	30	30	10	7	7	6	6
Sector V	Control	(0)	(30)	(30)	(30)	(50)	(50)	(D)	(D)	(D)
	4	1.5	35	35	35	32	32	32	30	30
	8	3	35	35	30	30	30	30	30	30
	12	5	35	35	30	30	30	30	30	24
5 days	16	6.5	35	35	30	30	30	30	30	15
	20	8	35	35	30	30	30	30	30	15
	24	10	35	35	25	25	25	25	25	15
Sector VI	Control	(0)	(70)	(70)	(70)	(70)	(D)	(D)	(D)	(D)
	4	1.5	75	75	75	75	75	75	75	50
	8	3	75	75	75	70	70	70	70	30
10 days	12	5	75	75	75	70	70	70	70	30
	16	6.5	75	75	75	70	70	70	70	25
	20	8	75	75	75	70	70	70	70	20
	24	10	75	75	75	70	70	70	70	20

* Experiment initiated 2/19/45.

Observations showed that, as in the previous experiment, losses in attached barnacles occurred roughly in proportion to the current velocity, although at no point of the disc was the entire set lost. Similarly, the limiting rate of flow necessary for inhibition of growth or for loss of attachment increased generally with the initial age of the barnacles. Since observations were made at intervals during the experiment it was also possible to note the period of rotation necessary to bring about the first losses in attachment. This also increased generally with increasing age of initial growth. The observations are set forth in detail in Tables V and VI and summarized in Table VII.

In Table V the number of barnacles per square inch is recorded for various distances from the center of the disc, and for each individual sector. These observations are repeated for various intervals of time during the experiment.

An increase took place in numbers on the control panels due to continued attachment of cyprids, whereas on the rotated disc barnacles became progressively reduced in number as the experiment continued. After one hour of rotation the only losses were among the six hour old barnacles on Sector I. These losses were very small, however, and although observed at current velocities of 1.5 knots and 10 knots, they did not occur at intervening velocities. The first significant losses took place twelve hours after the start of rotation among barnacles less than twelve hours old. Of the older ones, only those 5 days old showed losses, amounting to a change at most velocities from 35 to 30 per unit area.

Barnacles on the remaining sectors, varying in age from twelve hours upwards, were not observed to diminish in number until the third day of rotation. The smallest loss over this period took place among the twelve hour barnacles, which were only lost at speeds of ten knots, whereas, after a similar period of rotation, other barnacles of greater ages had been lost even at 1.5 knot current velocity. Ten day old barnacles were not greatly disturbed by 1.5 knot currents until after eleven days' rotation. These observations, summarized in Table VII, indicate that in general the velocity of current necessary to dislodge barnacles increased with the age they had reached before the experiment. Barnacles twelve hours old, however, showed a marked increase in resistance to being dislodged, even compared to those ten days old, whereas those two days old, on the other hand, seemed to be less resistant than younger or older ones. It is also noteworthy that in general the duration of rotation necessary to bring about the first losses depends much more upon the initial age of the barnacle than upon the current velocities.

In a similar manner the percentage of the original number of barnacles remaining following an eleven day period of rotation increased with increasing age before rotation. The ten day old barnacles at the end of the experiment, however, showed poorer resistance and had a lower percentage of continued attachment than in the case of the five day barnacles. It must be noted, however, that the ten day barnacles were densely crowded and it is possible that this factor decreased their resistance to dislodgement.

Further examination of the results in Table V discloses that losses continued to occur to some extent on all sectors at the end of eleven days, although they were less on those sectors where initial age of the barnacle was greater.

Observations of the size of barnacles recorded during the experiment are given in Table VI. On Sector I the six hour old barnacles within a diameter of 8 inches, equivalent to a three knot water current, continued to grow, although at a slow rate.

TABLE VI

*Growth of barnacles in relation to flow of water over the surface of a rotating disc, expressed as greatest diameter in millimeters **
(Figures in brackets refer to stationary control)

Stationary growth period	Diameter of disc (Inches)	Velocity (Knots)	Period of rotation							
			0 hrs.	1 hr.	12 hrs.	3 days	5 days	7 days	9 days	11 days
Sector I	Control	(0)	(0.3)	(0.3)	(0.3)	(0.5)	(0.8)	(1.3)	(2.5)	(3.0)
	4	1.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5
	8	3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
6 hrs.	12	5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	16	6.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	20	8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	24	10	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Sector II	Control	(0)	(0.3)	(0.3)	(0.3)	(0.6)	(0.8)	(2.5)	(3.0)	(3.5)
	4	1.5	0.3	0.3	0.3	0.3	0.3	0.3	1.0	1.5
	8	3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
12 hrs.	12	5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	16	6.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	20	8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	24	10	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Sector III	Control	(0)	(0.3)	(0.3)	(0.3)	(0.6)	(0.8)	(2.0)	(3.0)	(3.5)
	4	1.5	0.3	0.3	0.3	0.5	0.5	1.0	2.0	3.0
	8	3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5
1 day	12	5	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5
	16	6.5	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5
	20	8	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5
	24	10	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5
Sector IV	Control	(0)	(0.3)	(0.3)	(0.5)	(0.8)	(1.0)	(3.0)	(3.5)	(4.0)
	4	1.5	0.3	0.3	0.5	1.0	1.0	1.3	1.3	1.5
	8	3	0.3	0.3	0.3	0.8	0.8	0.8	0.8	1.0
2 days	12	5	0.3	0.3	0.3	0.8	0.8	0.8	0.8	1.0
	16	6.5	0.3	0.3	0.3	0.3	0.8	0.8	0.8	0.8
	20	8	0.3	0.3	0.3	0.3	0.8	0.8	0.8	0.8
	24	10	0.3	0.3	0.3	0.3	0.8	0.8	0.8	0.8
Sector V	Control	(0)	(0.8)	(1.0)	(1.5)	(2.5)	(3.0)	(4.0)	(5.0)	(6.0)
	4	1.5	0.5	0.8	1.0	2.5	2.5	3.0	3.0	3.5
	8	3	0.5	0.8	0.8	1.5	1.5	1.5	1.5	1.5
5 days	12	5	0.5	0.5	0.8	1.5	1.5	1.0	1.5	1.5
	16	6.5	0.5	0.5	0.8	1.5	1.5	1.0	1.5	1.5
	20	8	0.5	0.5	0.8	1.5	1.5	1.0	1.5	1.5
	24	10	0.5	0.5	0.8	0.8	0.8	0.8	0.8	0.8
Sector VI	Control	(0)	(2.5)	(2.0)	(2.5)	(4.0)	(5.0)	(7.0)	(9.0)	(9.0)
	4	1.5	2.0	2.0	2.0	3.5	3.5	4.5	4.5	5.0
	8	3	2.0	2.0	2.5	3.0	3.0	3.5	3.5	3.5
10 days	12	5	2.0	2.0	2.0	3.0	3.0	3.5	3.5	3.5
	16	6.5	2.0	2.0	2.0	3.0	3.0	3.5	3.5	3.5
	20	8	2.0	2.0	2.0	3.0	3.0	3.5	3.5	3.5
	24	10	2.0	2.0	2.0	3.0	3.0	3.5	3.5	3.5

* Experiment initiated 2/19/45.

TABLE VII

Summary of observations on the effect of water currents produced by rotation upon attached barnacles. Expressed as multiples of normal growth, period before loss in number first occurred, and percentage remaining at the end of eleven days *

Current velocity (Knots)	Period of stationary growth					
	6 Hrs.	12 Hrs.	1 Day	2 Days	5 Days	10 Days
1.5	0.1 × (1 Hour) 20%	0.4 × 5 Days 30%	0.8 × 3 Days 30%	0.3 × 3 Days 50%	0.6 × 3 Days 90%	0.6 × 11 Days 70%
3	*Inhibition* 12 Hours 30%	*Inhibition* 5 Days 40%	*Inhibition* 3 Days 40%	0.3 × 3 Days 60%	0.2 × 2 Days 90%	0.3 × 3 Days 40%
5	— 12 Hours 20%	— 5 Days 20%	— 3 Days 30%	0.1 × 3 Days 30%	0.2 × 2 Days 70%	0.3 × 3 Days 40%
6.5	— 12 Hours 20%	— 5 Days 20%	— 3 Days 20%	*Inhibition* 3 Days 30%	0.2 × 2 Days 60%	0.3 × 3 Days 30%
8	— 12 Hours 20%	— 5 Days 20%	— 3 Days 20%	— 3 Days 20%	*Inhibition* 2 Days 60%	0.3 × 3 Days 30%
10	— (1 Hour) 10%	— 3 Days 20%	— 3 Days 20%	— 3 Days 20%	— 2 Days 60%	0.3 × 3 Days 30%

* Experiment initiated 2/19/45.

Even at velocities below 1.5 knots the growth was considerably less than that of the stationary control. The ten day old barnacles on Sector VI continued to grow near the circumference, although subjected to ten knot currents. Barnacles of intermediate age showed a reduction of growth inversely dependent upon their initial age, and directly dependent upon the current. Barnacles less than two days old ceased growth at water currents over three knots, and only the ten day old barnacles continued growth at ten knots.

At the end of this experiment the remaining barnacles were examined to determine whether any considerable portion remaining attached was dead. A few of the older barnacles had lost their soft parts, but it was difficult to obtain a reliable criterion as to the condition of the remainder. It was not definitely established, therefore, what proportion had died.

Differences between the results of this and the previous experiment lie mainly in the higher current velocities required to bring about growth inhibition and loss of attachment and the absence of complete loss at any part of the disc in the later experiment. This apparent anomaly may be partly due to the much greater density of initial attachment, which may have reduced the *effective* velocity of the currents by providing a much more irregular surface. It is also conceivable that had the experiment continued for the full 19 day period of the first experiment rather than 11 days only, the growth inhibition effect might have appeared at lower velocities and might have resulted in complete loss at some parts of the disc.

Discussion

The experimental results indicated that current velocities limiting the attachment of barnacles lie in the neighborhood of one knot and that the limits for the three species, *Balanus eburneus, B. amphitrite,* and *B. improvisus* are in ascending order of magnitude. That a one knot current should limit attachment is in accordance with the conclusions of Visscher and earlier workers that attachment of barnacles does not readily take place upon ships in motion.

It further appears that growth rates of previously attached barnacles are reduced by water currents in inverse proportion to the age of the barnacle and directly in proportion to the current velocity. The effect of crowding together is further to reduce the growth rate. The effect of very low current velocities is to increase the rate of growth. A slight loss of attachment occurs at all current velocities, but this may be partly due to overcrowding. Large and significant losses take place at velocities which are sufficient to reduce the growth rate. These losses begin some hours after the start of rotation, and continue for a period of at least eleven days.

Since losses due to dislodgement do not occur during the first few hours of rotation, except in the case of barnacles attached within six hours or less, and since they continue to take place during the entire period of rotation, it seems probable that they are not directly due to mechanical action. Possibly the mechanism is one of interference with feeding processes, followed by reduced growth rate, death and diminished adhesion.

A further point arising out of the experimental data is the fact that at equivalent current velocities 12 hour and 24 hour old barnacles show greater growth and less loss of attachment than those somewhat older. It is possible that at this stage of development, with metamorphosis incomplete, an orientation to the current may occur which facilitates feeding, although this was not actually observed.

Once attached the barnacles are able to withstand current velocities of increasing magnitude, although for the first two or three weeks the growth rate is considerably reduced. Loss of attachment appears to follow reduced growth rate and may involve actual death from lack of food. The current velocities required to bring this about are sufficiently low to provide support for Visscher's conclusion that barnacles are killed by ocean passages of 500 miles or more, if vessels of more than 10 knots performance are considered, or if the age of attached barnacles is no greater than a 10 day stay in port would allow. On the other hand, current velocities lying below this figure, such as would be produced by slow sailing vessels, would appear from the experimental data to be insufficient to bring about a loss of the attached barnacles. In the case of faster ships, stays in port of longer than a few days might also permit the accumulated barnacles to survive an ocean passage. This type of ship service would readily provide a means of distribution for barnacles. It would explain Fischer-Piette's observations of the appearance of *Balanus amphitrite* on Mediterranian shores, and would support his hypothesis of distribution by ships.

The enhanced growth rate in current velocities of 1.3 knots and less, depending on the age of the barnacle, provides a quantitative expression for the observations of Rice, Moore, Kitching, and others upon the increased growth of barnacles subjected to water currents.

The conditions in a harbor or an embayed or open coast are rarely such that tidal currents in excess of one knot are continuously present. Under these conditions, therefore, there would be no obstacle to the attachment of barnacles. Once attached, however, the barnacles would usually be subjected to intermittent tidal currents.

No data are available as to the effects of intermittent currents but it would be reasonable to assume that these would be, if anything, less than the effects of continuous currents. The data presented here would therefore make it appear unlikely that any but the strongest of tidal currents would prevent the attachment and continued development of barnacles on rocks or stone, and wooden piling. Where fairly continuous currents of less than 1.5 knots were present the growth would be encouraged.

A different situation occurs in estuaries where continuous currents might occur. Here, however, the limiting factor, according to the work of previous authors, is probably lowered salinity, since continuous currents would scarcely permit of the estuary remaining salt.

Where wave action is strong the effects might be considered as equivalent to strong currents of frequently changing direction, which might conceivably inhibit attachment or growth, even below tide levels. Even where attachment occurred during temporary lulls, the strong recurrent wave action might be expected to dislodge the barnacles. This may explain the observations of Stephenson and his co-workers that some species of barnacles do not occur in a zone of heavy wave action.

The effect of water currents under natural conditions may therefore be summarized as one of enhanced growth with velocities below 1.5 knots, and one of reduced growth above this. It would rarely happen under natural conditions that water currents alone would prevent barnacle colonization. Strong wave action, however, might be expected to have this effect.

Certain qualifications should be added to the above discussion which may explain some anomalous observations. The arguments above are based on the calculated rates of flow of water over the rotating disc, and the results of experiments have indicated that these rates are slightly higher than the actual rates of flow taking place. The error, however, does not appear to be greater than 10 per cent to 20 per cent, and does not qualitatively affect the validity of the general conclusions.

Since the observations were made upon the relatively smooth surface of a wooden disc, they would not be applicable to very rough surfaces where local pockets of relatively still water might develop, to the areas immediately adjacent to lapped plates of ships' hulls, or to portions of piling or other submerged surfaces where the contours and configuration might produce local stagnation effects.

Summary

1. The work of previous authors, dealing with the effect of water currents upon barnacle attachment, growth and distribution is briefly reviewed.

2. Experiments were conducted to determine the effects of water currents upon the attachment and growth of barnacles, and particularly of *Balanus amphitrite*.

Submerged rotating discs and glass tubes of graded cross-sectional diameter were employed to provide variations in current velocity.

3. The velocity of water current limiting attachment appears to lie between 0.5 and 0.9 knot for *Balanus amphitrite,* between 0.4 and 0.7 knot for *B. eburneus,* and above 1.1 knots for *B. improvisus.*

4. Following attachment the growth rate of barnacles was found to be increased by water currents of velocity less than 1.5 knots and to be decreased by currents with velocities in excess of this. The adverse effects of water currents were found to decrease with increasing age of the barnacles subsequent to attachment. Six hours after attachment, growth rate was reduced to one-third of normal by a 1.5 knot current and completely stopped by a 3 knot current. Five days after attachment, growth was prevented by currents ranging between 3.3 and 8 knots.

Loss of attachment appeared to some extent among all barnacles in which growth rate was reduced. This loss was greatest at velocities bringing about complete cessation of growth.

5. It is suggested that loss of attachment is due to interference with the feeding process, followed by reduction of growth rate, death, and diminished adherence. Possibly due to an orientation to the current which facilitates feeding, barnacles attached for one day or less show less retardation of growth rate and loss of adherence than barnacles two days old.

6. Since tidal currents are almost invariably intermittent it appears from the data presented that they are not sufficient to prevent the colonization of suitable surfaces by barnacles, except where the velocities are unusually high.

It also follows from the numerical results obtained that on vessels making short stays in port and relatively long voyages, little permanent barnacle fouling will occur, since those organisms which attach will be killed and at least a portion of them dislodged. The evidence does not preclude, however, the continued growth of barnacles upon slow vessels making longer stays in port, and their geographical distribution by this means.

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THE OCCURRENCE OF A DIABETOGENIC FACTOR IN THE EYESTALKS OF CRUSTACEANS *

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During an investigation of an endocrine influence on carbohydrate metabolism of crustaceans, it was found that aqueous extracts of the eyestalks produced within a very short time an intense hyperglycemia in the blue crab, *Callinectes sapidus*. This observation had been made several weeks previously by Mr. J. Armstrong [1] in the crayfish, and it now appears that a diabetogenic factor may exist in the eyestalks of the decapod crustaceans at least, and that it may be an agent in the normal regulation of sugar metabolism in this group of animals.

Of the common large decapods of the Woods Hole area the lobster has been found to be a very suitable form for such an investigation, but owing to legal difficulties in obtaining this species the blue crab was used. Blood was obtained by heart punctures made through a small hole drilled in the carapace, and subsequently analyzed by the method of Miller and Van Slyke.[2] The use of an anticoagulant was found unnecessary. The blood sugar values represent the total reducing substances, and for the present no distinction between fermentable and nonfermentable sugar was made. The amount of blood withdrawn for each analysis was 0.5 cc.

The blood sugar values of crabs freshly brought into the laboratory vary considerably. As an example, the individual values of seven crabs were 16, 112, 52, 18, 60, 27 and 55 mgs. per cent. This considerable variation is due to the handling of the animals, for it disappears when the crabs are segregated into separate containers and left undisturbed. After 5 days of isolation and starvation, the blood sugar values fell gradually, so that on the fifth day the individual readings of the five crabs showing the highest of the above values were 25, 24, 22, 24 and 21 mgs. per cent. Excess handling of the animals or other forms of excitement tends to induce hyperglycemia even after segregation and fasting. Consequently, blood samples were obtained as rapidly as possible and with a minimum of disturbance to the animals. When extracts were to be tested for glycemic effects, the animals were always separated into individual containers and starved for at least 5 days previously.

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* Contributions from the Woods Hole Oceanographic Institution, No. 329.

[1] Personal communication.

[2] Miller, B. F. and D. D. Van Slyke, 1936. *Jour. Biol. Chem.*, **114**: 583.

1. The Effect of a Single Injection of Eyestalk Extract

Twenty-one crabs were prepared as previously described. The average blood sugar value for this group was 20 mgs. per cent. The animals were divided into four groups of five animals each, so chosen that the average value of each group was 20 ± 1–2 mgs. per cent. Into each animal, 0.2 cc. of a sea-water soluble fraction of the eyestalks of *Uca pugilator* was injected, this volume being equivalent to one Uca eyestalk. Blood samples were taken from the first group one hour following injection, from the second group 2 hours after injection of this group, from the third at 3 hours after injection, from the fourth 4 hours after injection, and again from the first group 5 hours after the injection of this group. The results of this experiment are shown in Figure 1. The diabetogenic effect of the eyestalk extract is not due to reducing substances contained in the extract for, in the above experiment, the amount of extract injected into each animal contained only 1.3 mgs. per cent reducing substances calculated as glucose.

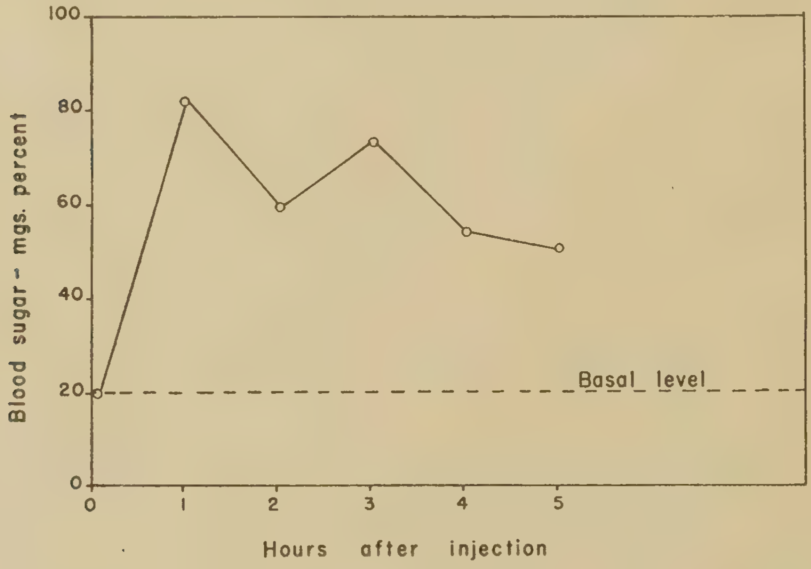

Figure 1. Curve showing the effect of a single injection of eyestalk extract (Uca) on the resting blood sugar level of the blue crab.

2. The Effect of Dilution on the Diabetogenic Action of Eyestalk Extracts

Eyestalks of *Uca pugilator* were ground thoroughly with a small amount of seawater, the soluble portion decanted, and the residue re-extracted twice in the same fashion. The combined soluble portions were centrifuged, and from the supernatant solution a series of dilutions ranging from 5 E.S.[3]/cc. of solution to 0.005 E.S./cc. solution was made. The amount of material injected into the test animals prepared as described above, was in all cases 0.2 cc. Blood samples were withdrawn from each specimen one hour following the injection. The results of this experiment are shown in Table I. It is evident that a rough agreement between dosage and the resulting hyperglycemia exists, the greatest dose producing the greatest increment. However, there is little difference in the values obtained among the doses ranging from 0.1 E.S. to 0.001 E.S. The greatest response produced was a four-fold increase (1.0 E.S.) but it should be remarked that five- and six-fold increments in blood sugar values have been obtained with extracts of the eyestalks of Callinectes in the same, or even smaller doses. Injection of sea-water was without effect, the slightly higher value (24.5 mgs. per cent) for this group over the uninjected controls (20.0 mgs. per cent) being statistically insignificant. The extract was active in the lowest dosage given (0.001 E.S.) since the value obtained (41.6 mgs. per cent) represents a significant difference over either the uninjected or the sea-water injected control groups. However, some of the readings obtained with higher doses are not significant, this being due to the large standard deviation.

TABLE I

The effect of dilution on diabetogenic activity of the extracts

Number of animals injected	Dosage of extract	Blood sugar values—mgs. %
5	1.0 E.S.	82.4 ± 5.1
4	0.5 E.S.	59.5 ± 10.3
8	0.1 E.S.	49.5 ± 5.5
5	0.05 E.S.	47.0 ± 6.2
7	0.01 E.S.	46.4 ± 11.1
10	0.001 E.S.	41.6 ± 3.9
12	0.2 cc. sea water	24.5 ± 2.3
18	uninjected controls	20.0 ± 1.6

3. THE EFFECT OF BOILING ON THE DIABETOGENIC EFFECTS OF THE EXTRACT

Concentrated aqueous extracts of Uca eyestalks were divided into halves, one of which was placed in a water bath at 100° C. for several minutes, and the other left untreated. After heat coagulation, the boiled extract was centrifuged and the supernatant fluid diluted to the original volume before boiling. Both boiled and unboiled extracts were greatly diluted with sea-water so that each animal was injected with 0.2 cc. of a dilution containing 0.5 E.S./cc., or 0.1 E.S. total dose per animal. Blood samples were taken as usual one hour following injection. No difference was found in the activity of the boiled and unboiled extracts (Table II).

4. LOCALIZATION OF THE DIABETOGENIC ACTIVITY OF THE EYESTALK

Four eyestalks of the blue crab were opened by a longitudinal incision, and the sinus gland of Hanström dissected out.[4] The glands were macerated in 4 cc. of

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[3] The letters E.S. are used as an abbreviation of eyestalk.

[4] The position of the sinus gland was kindly demonstrated by Dr. F. A. Brown, Jr.

TABLE II

The heat stability of the diabetogenic factor

Dosage	Number of animals injected	Average blood sugar values—mgs. per cent	
		Boiled	Unboiled
0.1 E.S.	4, 4	56	53
0.1 E.S.	6, 6	61	54

sea-water and centrifuged. 0.25 cc. of the extract was injected into each of four animals, the amount being equivalent to one-fourth of a sinus gland. The eyestalks from which the sinus glands were removed were also macerated with 4 cc. of sea-water, centrifuged, and 0.25 cc. of the extract injected into each of four test specimens. One hour after injection, the average blood sugar of the group receiving the sinus gland extract was 83 mgs. per cent, and that receiving the eyestalk (minus sinus gland) extract was 30 mgs. per cent.

5. EFFECTS OF EXTRACTS OF OTHER TISSUES

Saline extracts of the hepato-pancreas of the blue crab were without effect on the resting blood sugar level. Similar extracts injected into specimens made hyperglycemic (100–120 mgs. per cent) by various means produced variable results; in two cases, a sharp fall was obtained while in the majority of cases insignificant changes were observed.

6. THE EFFECT OF EYESTALK EXTIRPATION

Twenty-four crabs were isolated and starved for 3 days, after which time the eyestalks were surgically removed from 12 animals, the other 12 remaining as controls. The animals were then starved for another 7 days during which three sets of analyses were obtained from both normal and operated groups, on the second, fifth and seventh days following operation. The results are shown in Table III.

TABLE III

Animals	Blood sugar—mgs. per cent		
Days after operation	2	5	7
Normal (12)	22.6 ± 1.5	25.2 ± 4.5	22 ± 1.6
Operated (12)	24.4 ± 1.6	36.7 ± 4.6	40.3 ± 10.2

The blood sugar of the operated specimens tends to increase following the removal of the diabetogenic factor of the eyestalks, but the differences between the two sets of animals are not significant due to the large standard deviation. The results, however, seem paradoxical to those obtained from injection experiments, but it must be remembered that the operative injury may be sufficient to produce these high and irregular values and thus to mask any possible hypoglycemia resulting from the removal of the eyestalk factor. This experiment should therefore be repeated with animals from which the sinus gland only is removed.

SUMMARY

A powerful diabetogenic factor has been found in aqueous extracts of the eyestalks of crustaceans. The activity of the extracts is interspecific, heat stable, and effective over a wide dilution range. The sinus gland of Hanström appears to contain most of the diabetogenic factor.

Contribution No. 330

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A QUANTITATIVE SURVEY OF THE INVERTEBRATE BOTTOM FAUNA IN MENEMSHA BIGHT

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Extensive qualitative surveys of the marine invertebrate bottom dwelling organisms in the Woods Hole area have been carried out by Verrill (1873), Sumner, Osborn, and Cole (1911), Allee (1923), and several other investigators, but quantitative methods have not been used in the study of the fauna of this region. A study was therefore begun in order to examine in a quantitative manner the more common marine invertebrate organisms occurring within a restricted area of the bottom of the Woods Hole region.

For the purposes of this evaluation, it was decided to examine the bottom fauna of Menemsha Bight. There are two primary reasons for this choice. In the first place, Menemsha Bight is a relatively well defined body of water formed by an indentation of the western shore of Martha's Vineyard island between Gay Head and Cape Higgon, near the western end of Vineyard Sound (Chart 1). Secondly, the flounder which are captured in the Bight during the months of July, August, and September are of considerable economic importance. Therefore, it is of interest to know in what manner the bottom fauna enters into the general food cycle of the area. Either the direct or the indirect food relationships of this fish may be influenced by changes in the number and type of smaller animals living on and in the bottom. This may in turn affect the length of season when the fish are present in the region and perhaps underlie annual fluctuations which occur in their abundance.

The present survey is a preliminary attempt to investigate these problems in a quantitative manner. In addition to determining the various common species of animals present in the bottom fauna, an attempt is made to establish their numerical distribution over the area. The wet weight of each catch and dry weight of the combustible organic matter that it contained are also determined as a rough index of the possible potential food supply which the different categories of animals represent.

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[1] Contribution No. 330.

[2] It is a pleasure to thank Dr. George L. Clarke for his aid in this problem. His stimulating interest was a source of much encouragement to the author.

Quantitative studies of the invertebrate marine bottom fauna in flounder fishing grounds have been made by several European investigators. The work of Petersen (1911, 1915, 1918), Jensen (1919), Blegvad (1914, 1925), and others in the Danish fishing grounds is well known. Davis (1923, 1925) has made several quantitative studies of the bottom fauna in the deep water fishing areas of the North Sea, while Idelson (1930) has carried out comparable investigations on the Spitzbergen Banks. In the western hemisphere, however, the extensive quantitative studies of marine bottom fauna have been restricted chiefly to the Pacific coastal regions (Shelford and Towler, 1925; Shelford, Weese, *et al.*, 1935; Weese and MacNab, 1930) while the several investigations of bottom animals along the Atlantic coastline have been largely of a qualitative nature.

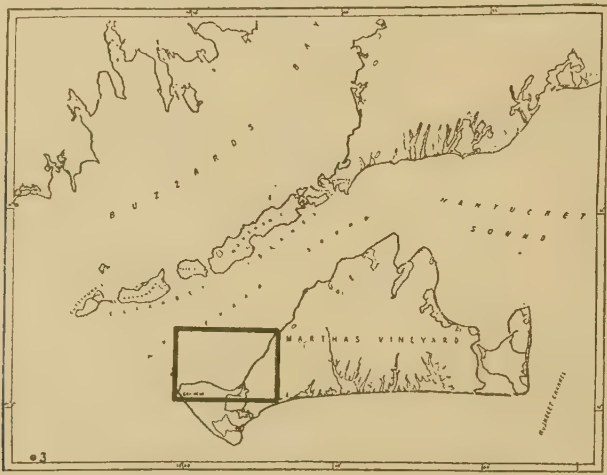


CHART 1. Map of Vineyard Sound and the adjacent islands. Menemsha Bight is the area enclosed by a heavy black line on the western end of Martha's Vineyard.

METHODS

Apparatus

Many previous investigators have found that the Petersen dredge (Petersen, 1911) was the most satisfactory bottom sampler devised to date for the purposes of their work. Preliminary trials of this instrument on sand, mud, gravel, and stony bottoms in Vineyard Sound, however, reveal that this dredge is highly unsatisfactory for quantitative sampling in this region, for it is relatively small and due to its lack of weight the jaws of the bucket frequently fail to penetrate the bottom deeply enough to obtain a sample or to capture other than organisms living upon the surface of the bottom. For these reasons, a larger and heavier dredge of the so-called "clam shell" design was purchased from the Hayward Company of New York. This instrument, made of special rust-resistant steel, weighs over 300 pounds when empty and covers a section of the bottom 101 × 56 cms. in area with its jaws open. It digs to a maximum depth of 23 cms. and holds 56 liters of material (wet sand) when level full. The single cable used in operating the bucket is tightly fastened to and winds about a counter-balanced revolving drum in the frame of the instrument. When the cable is hauled taut, the drum rotates and closes the jaws of the bucket. The drum turns in the opposite direction and opens the jaws when strain is removed from the closing cable. Thus a releasing hook inserted into the cable at a suitable point supports the weight of the instrument, with the terminal closing cable slack and the jaws open, during the descent to the bottom.

When removing animals from samples of bottom material of the size which this dredge obtains, manual sorting of the entire contents is impractical. Therefore, the material was poured into a hopper provided with a set of three removable screens which had pore spaces of 18.0, 10.0, and 1.8 mm. respectively. The sample was washed down through the screens, each of which withheld a fraction of the catch and thus prevented the coarser material from collecting in the final screen to crush the smaller, more delicate, organisms. A comparable method of removing animals from samples of bottom material has been used with success by Petersen (1911, 1913), Blegvad (1925, 1928), and Davis (1923, 1925).

The plan of the survey

It was considered impractical, due to strong tidal currents in Menemsha Bight, to attempt a grid-work of stations over the area. Instead, the stations were made in a series of five profiles extending offshore from the 2.5 meter depth contour along a compass course, with the samples taken at definite intervals. Two additional lines of stations were made roughly parallel to the shoreline (Chart 2). The close spacing of stations along such profiles gives more accurate information on the variability of bottom types and faunal aggregations than would be obtained from a series of stations scattered over the area; and it also permits ready location and resampling at any desired station. This "contour" method has been employed by Davis (1923) who found it especially useful where the organisms existed in patches or restricted regions of the bottom.

TABLE I

Variation among 13 20-liter samples taken at 4-meter intervals in Zone 2

	Average number	Standard deviation
Total number of species	14	24%
Clymenella torquata	12	26%
Ampelisca macrocephala	19	18%

In order to establish the variations in catches which might be due to the sampling process, 13 samples of comparable size (20 liters in volume) were taken from a uniform area (Zone 2) at intervals of only 4 meters. It was found that the total number of species in each catch varied 24 per cent from the average of 14 per sample. The number of *Clymenella torquata* captured were 12 per average sample, with a standard deviation of 26 per cent; and the number of *Ampelisca macrocephala* averaged 19 per sample, with a standard deviation of 18 per cent (Table I). It is possible that these quantitative differences in the catch were due to an actual variation in the distribution of the animals over the bottom. In view of the restricted size of the region tested, however, it is assumed that the variations were caused by the sampling process itself. The average quantitative differences between the faunas of the various zones are much greater than these standard deviations of the catches in a restricted uniform area (Tables II and III). Therefore, it is believed that the quantitative data are reliable. Throughout the survey, single samples were taken at each station. Deevey (1941) found that the use of single sample stations offered satisfactory results in his studies of Connecticut lakes.

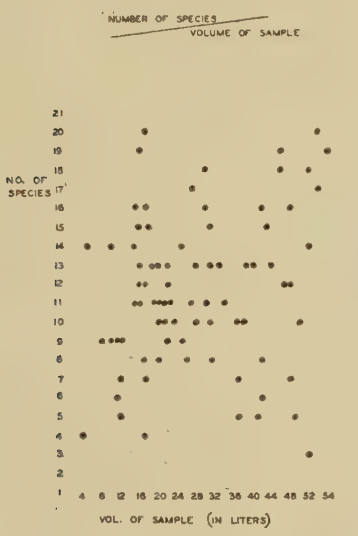
Analysis of material

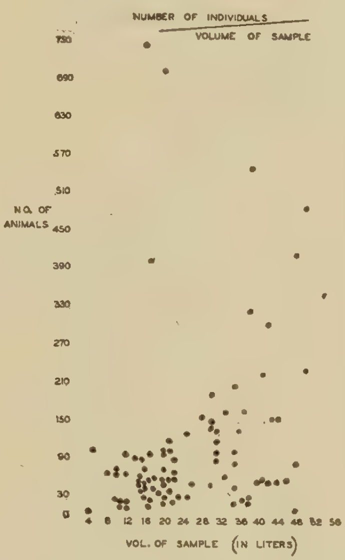
The catch from each station was brought into the laboratory where the organisms were identified and counted. The carapace of each large crustacean and the shells of all molluscs were removed and the wet weight of each catch was recorded (Davis, 1923; Berg, 1938). The estimated weight of all echinoderm tests was also subtracted from the weight of animals captured. The dry weight of the entire catch was obtained by drying the organisms to constant weight at approximately 120° C. The dried material was then ashed at approximately 650° C. By deducting the ash weight from the dry weight, an expression of the combustible organic matter present in the catch was obtained (Table III). The determination of organic content by this method is a customary procedure (Petersen, 1911; Juday, 1921; Birge and Juday, 1934).

Method of presentation of data

As in previous investigations of this nature by other investigators (Juday, 1921; Berg, 1938) it was found that the amount of bottom material obtained in the samples varied considerably, depending upon the relative hardness of the bottom and other conditions which affected the depth to which the dredge penetrated the bottom. However, there was no correlation between the size of the sample and the number of different species caught (Graph 1). In general, the larger samples of bottom material contained the greatest number of organisms (Graph 2). These facts support the assumption that the animals tend to be relatively uniformly distributed in the bottom material, at least down to the levels of the deepest grab of the dredge.

The invertebrate bottom organisms may be distributed vertically in the bottom sands in three different ways: 1. they may be restricted to a level at the surface of the bottom; 2. they may be uniformly distributed vertically throughout the bottom (down to the deepest grabs of the dredge); or 3. they may exist in greatest abundance at a level beneath the surface of the bottom material. If the first situation occurs, the quantitative data on the distribution of the organisms are best expressed on an area basis. This method has been used widely in quantitative marine studies, in spite of the variations in size of the samples obtained and although the vertical distribution of the organisms is not established. If the second situation obtains, the data should be expressed on a volumetric basis. This would eliminate variables introduced by samples of differing volume. If the third situation occurs, the choice between the area and the volumetric basis depends largely upon the numbers of animals existing between the levels of their greatest concentration and the surface of the bottom. In the present survey, the data presented in Graphs 1 and 2 support the second assumption. Therefore, the quantitative values for numbers of animals, wet weight of the catch, and the dry weight of the organic content obtained at each station have been calculated and expressed on the volumetric basis, using 20 liters of bottom material as the standard unit since most of the samples were of this size. The relative significance of the catch from samples of less than 10 liters or more than 40 liters in volume, when compared to that from samples more nearly approximating the standard size, is regarded as questionable, due to the large differences in volume. The data from such samples are not treated. The factor necessary to convert the data to expressions of the standard volume varied between the limits 0.5 and 2.0. Thus possible errors, should the uniform vertical distribution of organisms not occur at certain stations, would be relatively small in comparison with the variations in abundance of animals from station to station and from zone to zone.





GRAPH 1. The total number of species obtained in each sample, plotted against the volume of the sample in liters. It is apparent that there is no correlation between the size of the sample and the number of different species captured.

GRAPH 2. The total number of animals of all species in each sample, plotted against the size of the samples. In general, the larger samples contained the greater number of organisms.

In making comparisons with other investigations, it should be remembered that this standard unit (20 liters) represents a portion of the ocean bottom 0.5 sq. meters in area, and 10.0 cms. in maximum depth. It is assumed that organisms in the bottom material below this level are of questionable importance as components of fish diet.

Inclusion of the weight of large bivalve and gastropod molluscs in the data, in view of their probable insignificance as fish food (Blegvad, 1925), would produce distortion of the results if one wishes to determine the amount of food material available to bottom-dwelling fishes. Therefore, in order to give complete values for the catches in each zone, as well as to indicate their relative significance as a source of food to fishes, the data for each zone have been expressed in two ways: 1. with all organisms included (shells and estimated weight of echinoderm tests removed); and 2. with the weights of large molluscs (*Cyprina islandica, Polynices immaculata*), molluscs possessing thick shells (*Venericardia borealis, Astarte* sp.) and all echinoderms omitted. A somewhat comparable method of expressing data was used by Berg (1938) who presented his results with all organisms included, and also with molluscs omitted.

RESULTS

The ocean floor in Menemsha Bight can be divided into five major zones arranged approximately coincident with definite depth contours. Each zone is characterized by a distinct type of bottom material, and a distinctive faunal aggregation is associated with four of these types of bottom. Table II contains a list of the catch at two stations in each zone, per standard volume of bottom material. Table III shows the predominant types of bottom (and average values for the catches) in each zone. Table IV is a list of the most common animals found in the bottom sands of Menemsha Bight and their average number in standard samples from each zone.

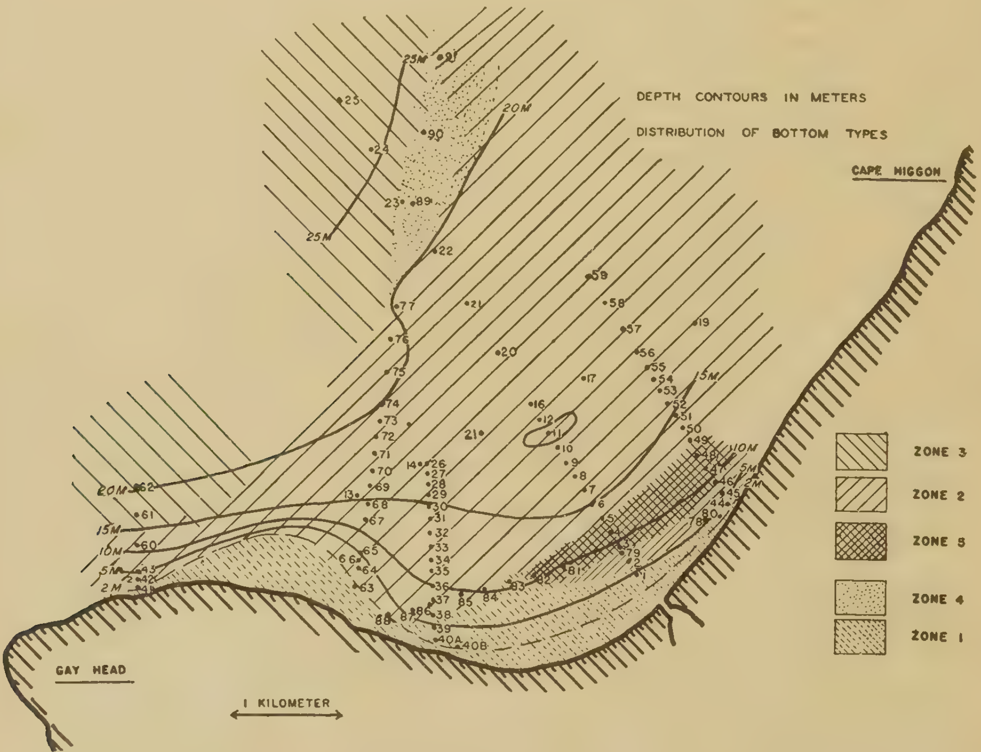

DEPTH CONTOURS IN METERS
DISTRIBUTION OF BOTTOM TYPES
CAPE HIGGON
GAY HEAD
1 KILOMETER
25M
20M
15M
10M
5M
2M
ZONE 3
ZONE 2
ZONE 5
ZONE 4
ZONE 1

CHART 2. The number and location of each station, and the extent of the five zones in Menemsha Bight. The depth contours, in meters, are indicated by solid lines, with the exception of the 2-meter contour which is shown by a line of dashes.

Table II

Typical catches from each zone

Zone 1.

Station 40-B	
Clymenella torquata	1 specimen
Glycera dibranchiata	6 specimens
Nephthys incisa	1 specimen
Ninoe nigripes	1 specimen
Scolopolus fragilis	3 specimens
Tellina tenera	10 specimens

Station 41	
Ampelisca macrocephala	1 specimen
Echinarachnius parma	1 specimen
Emerita talpoida	21 specimens
Nephthys bucera	1 specimen
Tellina tenera	19 specimens

Zone 2.

Station 26	
Astarte undata	3 specimens
Clymenella torquata	27 specimens
Gammarus locusta	6 specimens
Glycera dibranchiata	6 specimens
Lumbrinereis hebes	1 specimen
Maldane sp.	3 specimens
Unciola irrorata	4 specimens
Venericardia borealis	1 specimen

Station 27	
Ampelisca macrocephala	2 specimens
Clymenella torquata	9 specimens
Dolichoglossus Kowalevski	1 specimen
Gammarus locusta	3 specimens
Glycera dibranchiata	5 specimens
Lumbrinereis hebes	1 specimen
Maldane sp.	2 specimens
Nephthys incisa	1 specimen
Nephthys bucera	1 specimen
Ostrea virginica	1 specimen

Zone 3.

Station 24	
Ampelisca macrocephala	31 specimens
Callocardia morrhuana	3 specimens
Cirolana concharum	2 specimens
Clymenella torquata	1 specimen
Cyprina islandica	2 specimens
Echinarachnius parma	12 specimens
Nassa trivitata	1 specimen
Polynices immaculata	1 specimen
Scolopolus fragilis	1 specimen
Unciola irrorata	1 specimen
Venericardia borealis	4 specimens

Station 25	
Ampelisca macrocephala	22 specimens
Astarte quadrans	1 specimen
Cirolana concharum	1 specimen
Cyprina islandica	1 specimen
Echinarachnius parma	1 specimen
Marphysa sp.	1 specimen
Nephthys bucera	1 specimen
Polynices immaculata	1 specimen
Scalibregma sp.	1 specimen
Venericardia borealis	3 specimens

Zone 4.

The fauna of this zone was essentially similar to that of zone 3, in its quantitative and qualitative aspects.

Zone 5.

Station 48	
Amphitrite ornata	1 specimen
Astarte castanea	2 specimens
Astarte undata	1 specimen
Asterias forbesi	2 specimens
Callocardia morrhuana	1 specimen
Cancer irroratus	1 specimen
Chaetopleura apiculata	2 specimens
Cirratulus grandis	1 specimen
Crepidula fornicata	692 specimens
Lepidonotus squamatus	1 specimen
Marphysa sp.	1 specimen
Pagurus longicarpus	1 specimen
Phascolosoma gouldi	2 specimens
Pinnixia cylindrica	1 specimen
Trophonia affinis	10 specimens
Venericardia borealis	19 specimens

Station 81	
Arabella opalina	1 specimen
Arca transversa	2 specimens
Callocardia morrhuana	3 specimens
Cancer irroratus	1 specimen
Chaetopleura apiculata	1 specimen
Crepidula fornicata	353 specimens
Gammarus locusta	1 specimen
Lepidonotus squamatus	1 specimen
Libinia emarginata	1 specimen
Nereis virens	1 specimen
Pagurus longicarpus	7 specimens
Phascolosoma gouldi	1 specimen
Scalibregma sp.	1 specimen
Trophonia affinis	16 specimens

Table III

The wet weight of the catch, and the dry weight of the organic matter it contained, in the average standard-sized samples from each zone

Zone	Most numerous animals	Average wet weight of the catch in 20 liters of bottom material		Average dry weight of the organic content of the catch in 20 liters of bottom material	
		A[3]	B[4]	A[3]	B[4]
1	*Emerita Tellina Ampelisca*	5.6 gms.	1.9 gms.	0.9 gms.	0.33 gms.
2	*Clymenella Ampelisca*	27.2 gms.	10.0 gms.	2.6 gms.	1.3 gms.
3	*Ampelisca Cyprina*	164.0 gms.	9.8 gms.	29.4 gms.	1.0 gms.
4	*Ampelisca Echinarachnius*	73.0 gms.	6.3 gms.	10.7 gms.	0.5 gms.
5	*Crepidula*	364.0 gms.	360.0 gms.(?)	36.2 gms.	30.9 gms.(?)

Zone 1

Between the 2.5- and the 5-meter depth contours, the bottom is of a medium coarse yellow sand, containing a few small stones of pea size. An average standard unit of bottom material from this zone possessed five different species and a total of 32 animals of all species. *Emerita talpoida* and *Tellina tenera* were the most numerous organisms in this zone. The location of stations in this as well as in remaining zones is shown in Chart 2.

Zone 2

The coarser sands of Zone 1 graded rather abruptly (as shown by observations at stations 63–64; 38–39; 1–2; etc.) into fine mixed sands of white, yellow, and black color. This bottom material, called "Zone 2," was situated largely between the 5- and 20-meter depth contours, and extended over 80 per cent of the floor of the Bight. Annelids, small amphipods, and other organisms of known value as food for fishes were most numerous in this region, with *Ampelisca Macrocephala* and *Clymenella torquata* occurring in greatest numbers (Charts 2 and 4). The larger molluscs, however, such as *Cyprina islandica* and *Callocardia morrhuana* were more prominant by virtue of their relatively greater weight. The stations from this region which are shown in Table II illustrate the fact that the number of animals of a single common species (*Clymenella torquata*) may fluctuate 50 to 80 per cent from the average value in adjoining stations, when the number of such individuals caught is relatively low. It is seen in Table III that this zone was characterized by a heavier catch of organisms known to be of value as food for bottom dwelling fishes, than were the remaining zones.

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[3] Including all organisms.

[4] With the weight of large molluscs, molluscs with thick shells, and the estimated weight of echinoderms omitted.

The number of species taken in samples from this and from the remaining zones varied from six or seven at stations 32, 33, and 34, to 19 or 20 species at stations 76, 77, 21, 70, 71, 11, 58, 59, and 52. In general, however, the regions containing the greatest number of different species were found in Zone 2. By comparing Chart 3 with Chart 4, it is evident that these regions are also generally characterized by a great number of Ampelisca and Clymenella. In other words, in Menemsha Bight the individuals of a common species are generally more abundant in those areas where a large number of different species are found. Some of the possible factors which may determine the distribution of these organisms in Menemsha Bight will be treated in the discussion.

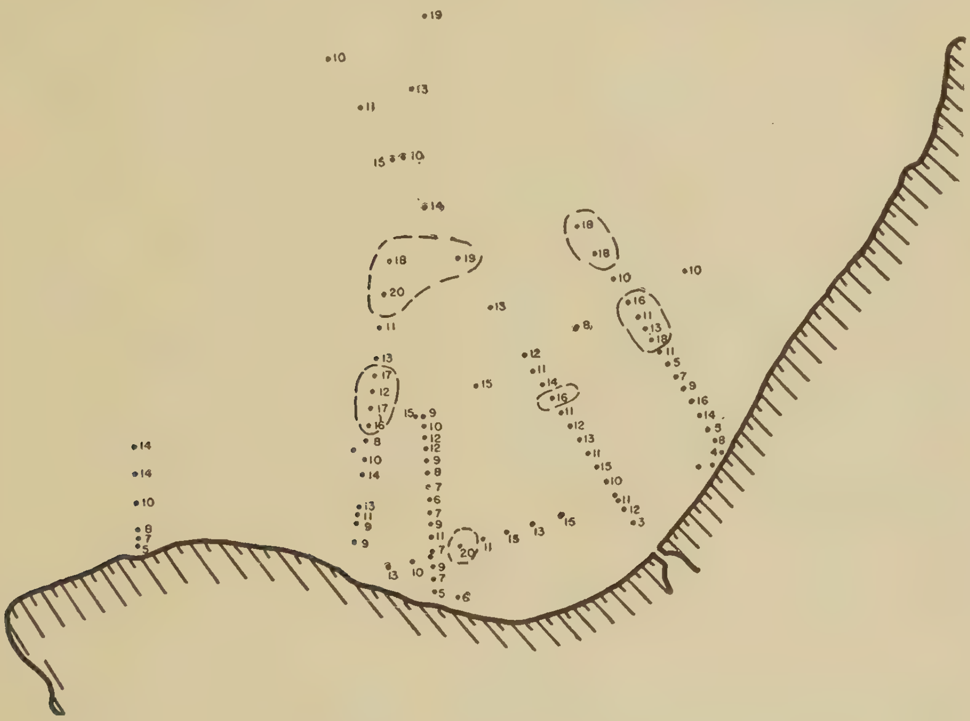
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Chart 3. The number of different species captured at each station. A line of dashes encloses each region where the number of species obtained was greater than 15/sample.

Zone 3

Beyond the 20-meter depth contour, the bottom was composed of loose, coarse sand, as shown by observations at stations 62, 24, and 25, which also contained shell fragments and small pebbles of various sizes. This zone contained a mixed fauna with amphipods and annelids present in each sample (Table II) but with no single species attaining numerical prominence. The large bivalve molluscs, such as Cyprina and Callocardia, composed the great bulk of each catch. It is interesting to note that *Cirolana concharum* and *Astarte quadrans* were found only at stations in this zone; whereas several organisms (*Echinarachnicus parma, Unciola irrorata, Scolopolos fragilis*) were also found in the coarse sand bottom of Zone 1, at much shallower depths.

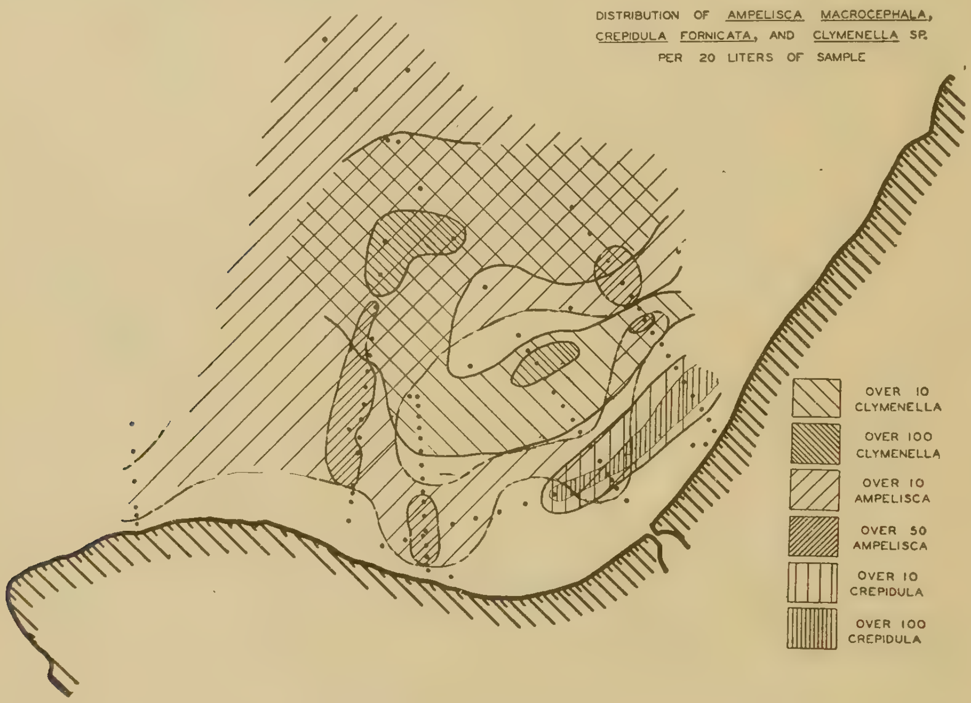
DISTRIBUTION OF AMPELISCA MACROCEPHALA, CREPIDULA FORNICATA, AND CLYMENELLA SP. PER 20 LITERS OF SAMPLE
OVER 10 CLYMENELLA
OVER 100 CLYMENELLA
OVER 10 AMPELISCA
OVER 50 AMPELISCA
OVER 10 CREPIDULA
OVER 100 CREPIDULA

CHART 4. The distribution of the three most numerous invertebrate animals in Menemsha Bight. The regions in which a common organism is most abundant are likewise characterized by a relatively greater number of different species (cf. Chart 3).

Zone 4

In the region about stations 89 and 90, a patch of medium grained white sand was discovered. There was little qualitative difference between the fauna of this zone and that found in Zone 3 (Table II). There was a slight quantitative difference, however, for the catches from Zone 3 were somewhat greater than those obtained from Zone 4 (Table III).

Zone 5

This zone was found between the 10- and the 14-meter depth contours along the eastern shoreline of the Bight (Chart 2). The bottom material of this region was of a soft fine clay, containing stones of walnut size and a considerable amount of nitrogenous matter near its surface. Mr. H. C. Stetson[5] informs me that this bottom deposit is probably of glacial origin, and contains very little marine sedi-

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[5] The author is indebted to Mr. Henry Stetson, Marine Geologist at the Oceanographic Institution, for his identification of the bottom material in the major zones of Menemsha Bight.

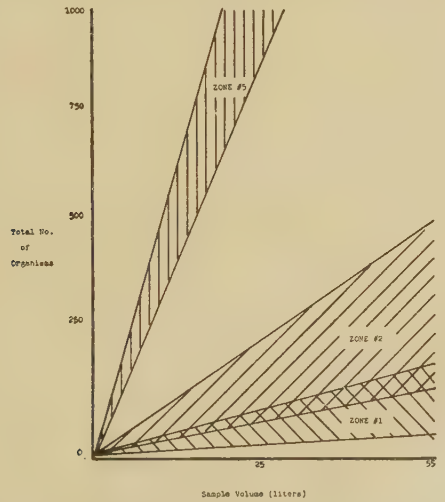
TABLE IV

The distribution of the eight most common organisms in Menemsha Bight (number of organisms/sample)

	Zone 1 15 stations	Zone 2 63 stations	Zone 3 5 stations	Zone 4 3 stations	Zone 5 5 stations
Ampelisca macrocephala	9	33	15	12	3
Clymenella torquata	0	35	1	0	0
Crepidula fornicata	0	0	0	0	423
Echinarachnius parma	3	1	4	6	0
Callocardia morruhuana	0	2	1	1	3
Cyprina islandica	0	0	4	1	0
Tellina tenera	9	0	0	0	0
Emerita talpoidia	8	0	0	0	0

ment. The bottom fauna of this region was composed of several types of crustaceans, annelids and molluscs; and the latter were predominant by number as well as by weight (Table II). *Crepidula fornicata* was exceptionally numerous and was restricted to this zone. *Trophonia affinis,* a burrowing annelid, was likewise found only in this bottom material. None of the remaining organisms was relatively abundant. The wet weight and the organic matter contained in the large numbers of Crepidula were included in the data presented in Table II although the relative importance of this organism as an article of fish diet has not yet been established. For this reason, the value for catches obtained from this zone is unusually high (Charts and Table II).

Table 4 shows the average number of the eight most common organisms obtained per 20 liters of bottom material in each zone. From these data it is possible



GRAPH 3. The total number of animals taken in each sample from the three major Zones, plotted against the volume of the sample in liters. (Fifty-five liters, the size of the largest sample, is the linear equivalent of 750 organisms.) The values for each of the Zones tend to occur within discreet regions.

to establish: 1. the numerical distribution of any one of these most abundant animals over the area; 2. the qualitative and quantitative aspects of the fauna of each zone, with respect to these organisms; and 3. the probability of capturing one or several of these organisms in a particular locality or type of bottom. The relative abundance within the zones of such organisms as Ampelisca and Clymenella and the restricted occurrence of Crepidula, Tellina and Emerita are clearly shown.

When the volume of bottom material obtained in each sample is plotted against the total number of organisms captured in that sample, it is evident that the larger samples tended to contain the greatest number of organisms (Graph 2). Graph 3 shows the relationship between the volume of the sample and the numbers of animals it contained, in the three major zones. It is interesting to note that the ratio between the size of the sample and the number of animals taken from it follows a distinctive trend in each region. The ratio ranges from 0.083 to 0.30 in Zone 1, with an average value of 0.11 (Graph 3). Similarly, the ratios for Zone 2 and 5 are 0.47 and 1.30 respectively. These figures afford a rapid means of comparing the relative abundance of organisms in each zone. In addition to their comparative value within Menemsha Bight, they offer a new method of expressing quantitative numerical relationships or comparisons between fauna of similar bottom types which may obtain in other localities. Other aspects of the bottom fauna of different regions (wet weight, content of organic matter, etc.) can likewise be compared in this fashion.

Discussion

It is apparent from a study of Charts 3 and 4 that the abundance of various species and the abundance of individuals of a single species varies considerably over the Bight. In general, the regions containing a large number of individuals of a single common species are also characterized by numerous different species. It can therefore be assumed that these regions probably offer an optimum of the conditions which determine the occurrence of these organisms. On the basis of this assumption, a closer study of these particular areas where the common animals in the Bight, such as *Crepidula fornicata* and *Clymenella torquata* are most numerous, should reveal certain of the factors which influence their abundance and distribution. Such a study is of particular importance, since many of these areas occur within that zone (2) which is by far the largest in the Bight, and which also contains the greatest numbers of animals known to be of value as food for bottom fishes.

The distribution of *Crepidula fornicata* apparently illustrates the role which the substratum may assume in determining the occurrence of an animal. This gastropod requires some relatively large hard object, such as a stone or shell, to which it fastens itself by the broad muscular foot. Such objects were found only in Zone 5, and these organisms were restricted solely to this region.

Another instance where the nature of the bottom material undoubtedly is of importance in governing the distribution of an animal, is shown by the occurrence of *Clymenella torquata* (Chart 4). This annelid is found largely in Zone 2, although a slight overlap exists to a coarser sand bottom at station 39, and to a softer bottom (which may also contain some fine sand) at stations 2, 79, 3, 4, and 5 (Charts 4 and 2). This organism constructs small tubes of the sand particles. From a comparison of the occurrence of the animal with the existence of a fine sand bottom, it would seem that these annelids may be limited to those regions of Menemsha Bight where the bottom material contains at least a certain amount of the optimum size sand particles.

The distribution of Clymenella in the Bight also suggests that its abundance in certain regions is associated in some manner with the depth of the water. At stations 76, 77, and 21, a standard unit of bottom material contained over 100 specimens, while at station 22 they were just below this number (Chart 4). These stations border the 20-meter depth contour, which is also the outermost (deeper) boundary of the fine bottom in Zone 2. At station 11, where the depth of water increased relatively suddenly from 15 to 21 meters, the number of Clymenella is over 10 times greater than that found at adjacent stations, where the depth was 15 meters. Thus it is possible that the depth of the water, in addition to the nature of the bottom, may influence the abundance of this organism. The relative scarcity of Clymenella at stations 15, 16, and 20, however, cannot be due either to the depth of water or the nature of the bottom material. Additional factors such as prevailing tidal currents, which are at present undetermined, may also influence the occurrence of this animal.

In addition to the qualitative and quantitative variation in the fauna of different zones and of different regions of the same zone, a fluctuation was also found in the numbers and species present in the fauna of adjacent stations over a uniform bottom (Chart 3). This variation is due primarily to two causes. In the first place, many of the organisms in the Bight are widespread, but they are also sparsely distributed (Cirratulus, Cancer, Callocardia, Libinis, Polynices, Limulus, etc.). The capture of several of these animals at one location, and their absence at the next, produced a considerable fluctuation in the number of species taken in each sample. As these organisms are also relatively large, their occasional occurrence likewise produced a variation of 10 to 20 grams in the wet weight and of 1 to 2 grams in the dry weight of the organic matter contained in the catches at adjoining stations. Secondly, it has been shown that the abundance of a single common species (*Clymenella torquata*) at two adjacent stations may vary 50 to 80 per cent from an average value, when the numbers of such organisms present in the region are relatively low (Table II). This fluctuation cannot be associated with any obvious characteristics of the environment, such as the depth of the water, or the nature of the substratum. It may represent an inherent tendency of the organisms to aggregate in certain arbitrary regions of the bottom, or it may be caused by environmental factors small enough to be completely overlooked in a survey of this general nature.

The bottom fauna of Menemsha Bight was similar to that found in European flounder fishing grounds, in that molluscs, annelids, and small crustaceans were the most numerous organisms. The molluscs of the European fisheries served as the chief article of food for the bottom dwelling teleosts in the region, with the annelids and the crustaceans as the next most preferred diet (Jensen, 1919; Davis, 1923; Blegvad, 1925, 1928, 1930). However, the actual food relationships which exist between the flounder and the bottom invertebrate fauna in Menemsha Bight have not been determined at present. During two trips over the region with a commercial fishing trawler, it was found that the flounder are taken in greatest number from two widely separated belts at maximum distances of 1.0 and 3.0 kilometers from the shore (Chart 5). It is evident that the abundance of flounder and that of Clymenella and Ampelisca (Chart 4) occur in relatively the same regions, but the actual nature of this relation remains to be established by further studies.

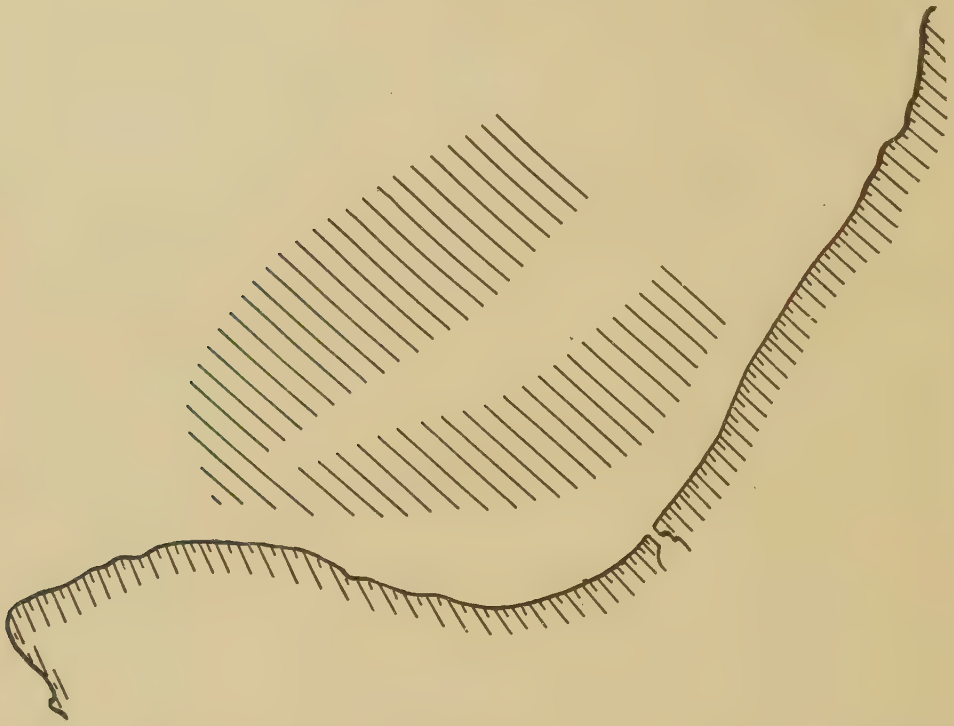


Chart 5. The diagonal lines indicate the regions of Menemsha Bight where the flounder are captured in greatest abundance. By comparing this chart with Chart 4, it is seen that these regions coincide in general with those areas where *Ampelisca macrocephala* and *Clymenella torquata* occur in large numbers.

Summary

1. A dredge which is larger and heavier than those employed previously in quantitative marine bottom sampling has been used with a specially designed screening device to facilitate the removal of organisms from the relatively large samples of bottom material.

2. The bottom of Menemsha Bight, a flounder fishing grounds in Vineyard Sound, is divisable into five zones on a basis of the bottom material. Four of the zones possessed a distinct faunal aggregation.

3. The zone which extended from the 5- to the 20-meter depth contour and contained a fine sand bottom occupied 80 per cent of the area of the Bight. This zone contained the greatest quantity of the animals (per unit volume of bottom material) that are generally known to serve as food for fishes. *Clymenella torquata* and *Ampelisca macrocephala* were the most common organisms. Flounders are caught in greatest numbers in the regions where these animals are most abundant.

4. The numerical distributions of *Clymenella torquata* and *Crepidula fornicata* are correlated with distinct characteristics of the bottom.

5. In general, the regions of the Bight containing an abundance of individuals of a common species also contain a large number of different species.

6. The fauna of adjacent stations in a relatively uniform area (Zone 2) may differ considerably in both qualitative and quantitative fashion. This variation is not associated with any observed environmental differences, such as the nature of the bottom material or the depth of water. It may represent the influence of minor factors, or of mechanical aggregation.

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Contribution No. 331

A THEORY OF SURFACE WATER MOTION DEDUCED FROM THE WIND-INDUCED MOTION OF THE PHYSALIA*

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For many years the author has wondered why the Portuguese Man-of-war (*Physalia pelagica* Bosc.) is so oriented physically that it is consistently driven by the wind about forty-five degrees to the left of the direction in which the wind is blowing[1] (Figure 46, left). Records kept of this leftward tendency showed little variation in distribution or time, within the limits shown in Table I. In the literature concerning this animal no explicit reference to this question of its motion relative to the wind and water has been found.

Physalia is a jellyfish of the order siphonophora which lives in the warm surface waters of the oceans. For the purposes of this discussion, its body may be considered as having two parts: the upper part a balloon-like float called a pneumatophore which is on the surface of the water, and the lower part a mass of tentacles which are attached to the ventral lee side (i. e., side opposite to direction of motion) of the float (Figure 46). Small fish and plankton, upon contact with these tentacles, are stunned by powerful stinging organs after which they are hoisted to the digestive zooids. During calm weather the tentacles may extend many meters below the sea surface, but when driven along by even a moderate wind these tentacles stream out behind the float with only a few centimeters of vertical extension. This means that the Physalia would necessarily "fish" through a relatively shallow layer near the surface while sailing. However, the large volume of water passing its tentacles when it is driven along by the wind should more than compensate for the lack of depth in its "fishing."

In speculating about reasonable explanations for this animal's persistent leftward motion, it was thought probable that the answer

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* Contribution No. 331 of the Woods Hole Oceanographic Institution.

[1] Hereafter, in all references to directions of motion on or within the surface waters concerned it will be assumed that the observer is facing in the direction toward which the wind is blowing.

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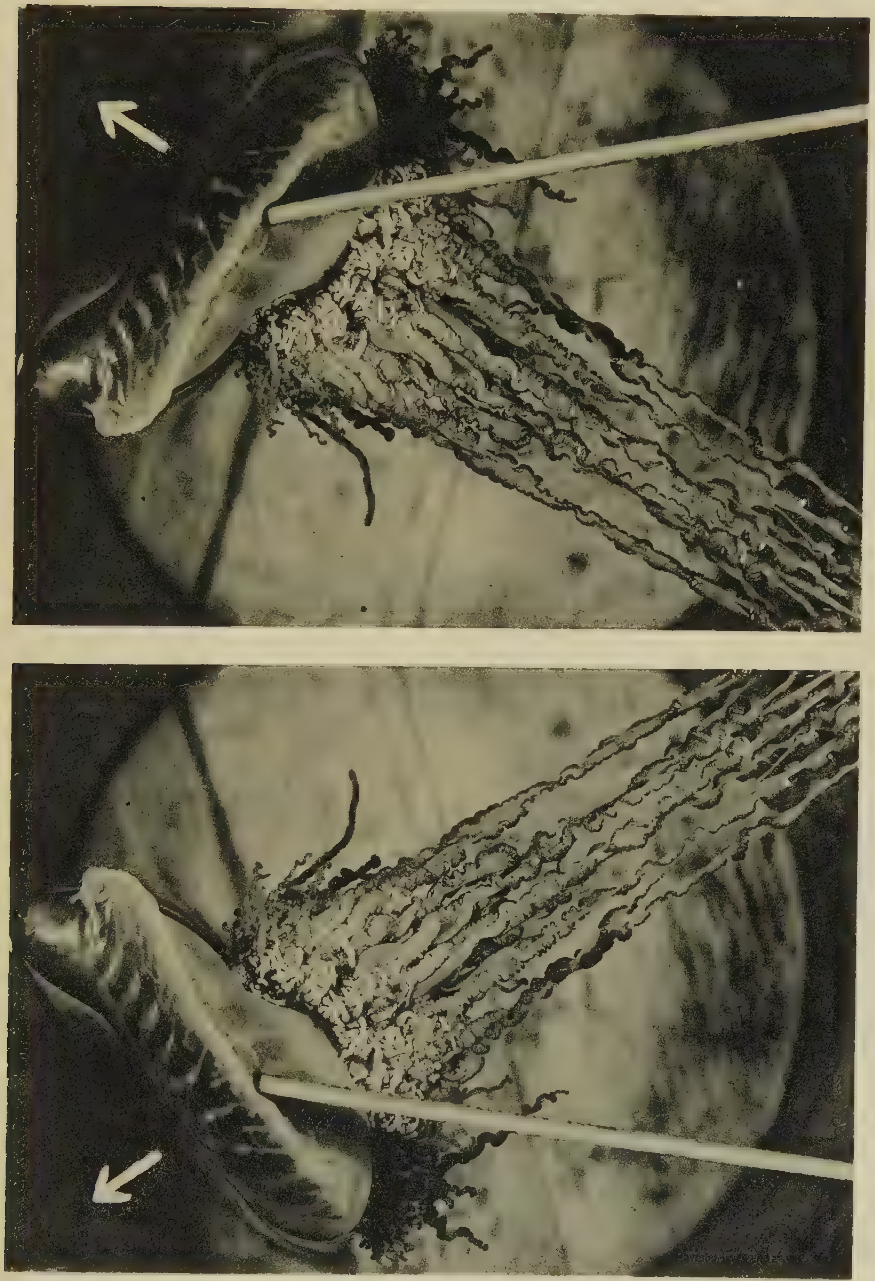

Figure 46. Laboratory photograph showing Physalia in sailing position, with tentacles streaming behind. For convenience, a mirror image of the northern hemisphere animal is used to represent one from the southern hemisphere. The rods indicate wind direction; arrows show resulting direction of motion: (left) in northern hemisphere and (right) in southern hemisphere.

TABLE I—PHYSALIA OBSERVATIONS AT SEA

Number of Physalia seen moving to:		*Date*	*Wind Force*	*Lat. N.*	*Long. W.*
*Left**	*Right**			*North Atlantic*	
2	0	Oct. 6, '39	3	39°22′	70°45′
1	0	Aug. 13, '40	–	39 23	72 28
1	0	Aug. 13, '40	–	39 23	72 28
13	0	Apr. 15, '41	4	33 31	74 52
1	0	Apr. 16, '41	3	29 26	74 42
1	0	Apr. 17, '41	3	25 29	72 24
2	0	June 28, '41	4	39 00	46 00
6	0	July 7, '41	4	39 00	46 00
2	0	Aug. 8, '41	2	40 18	67 21
3	0	Aug. 10, '41	5	36 26	64 08
34	0	Mar. 16, '42	3	26 36	80 00
11	0	Mar. 23, '42	5	25 42	80 06
				Gulf of Mexico	
113	0	Mar. 26, '42	5	26 27	84 25
89	0	Mar. 26, '42	4	26 42	84 47
76	0	Mar. 26, '42	4	27 00	85 10
37	8	Apr. 27, '42	4	27 29	86 35
29	1	Apr. 28, '42	5	27 55	89 32
421	9	Totals			

* Left and right of wind as illustrated in Figure 46.

would concern factors of survival such as the catching of food or the avoiding of danger.

In sections of the North Atlantic where the sargasso weed is common, the Portuguese Man-of-war is sometimes seen with tentacles hopelessly and fatally entangled in the weed. Since the weed is most often seen in lines formed parallel with the wind, it was thought possible that some characteristic of the motions of the surface water might cause a leftward-moving animal to avoid more of these lines of weed than a rightward-moving animal.

Langmuir (1938) made a study of formations of lines of drift in fresh water and found that these lines marked zones where surface waters are converging and sinking. "Midway between adjacent streaks" he found subsurface waters rising and diverging laterally (Figure 47A & B), so that under the action of winds the surface water was moving in a series of parallel left and right helical vortex pairs.

From Langmuir's measurements it became clear that the lines of sargasso weed, seen during winds on the sea surface, were collected in the convergent zones of similar vortex circulations. Thus, it was apparent that a Physalia sailing straight downwind would stay within a convergent zone and there encounter a maximum amount of entangling weed or other surface drift. However, this did not help in solving the problem of the animal's persistent leftward motion, for

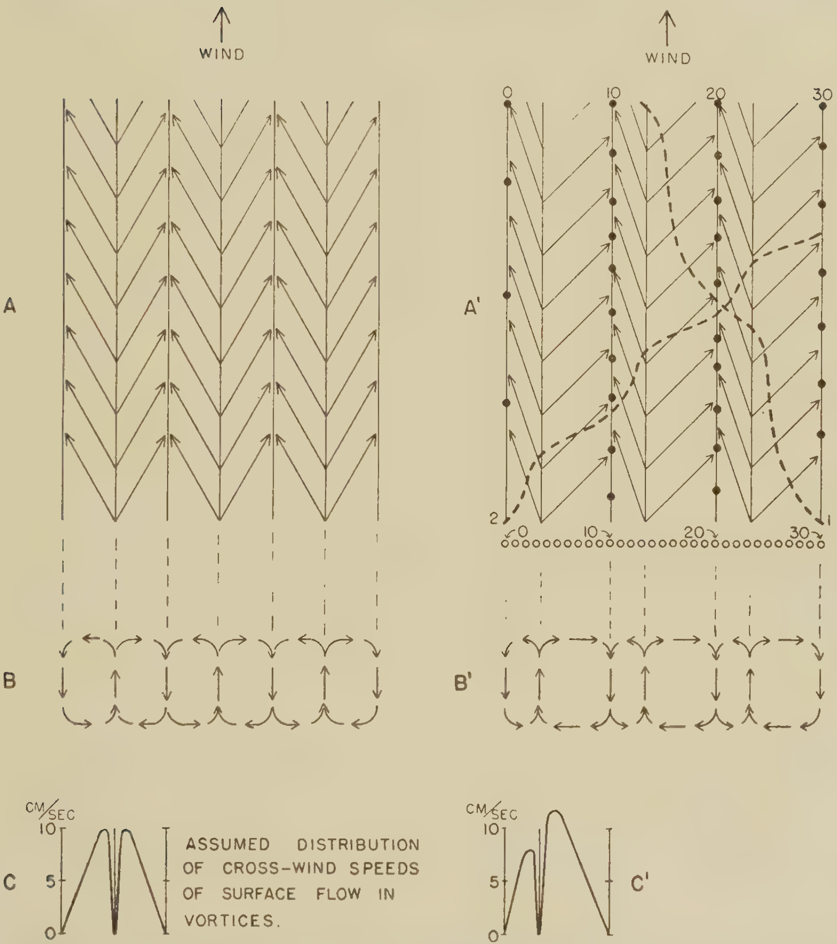
WIND
WIND
A
A'
0
10
20
30
2
1
0
10
20
30
B
B'
CM/SEC
10
5
0
C
ASSUMED DISTRIBUTION OF CROSS-WIND SPEEDS OF SURFACE FLOW IN VORTICES.
CM/SEC
10
5
0
C'

Figure 47. Idealized drawings of wind-induced helical motions in surface waters, with an illustration of the possible effect of asymmetrical vortices upon the drift of bottles and of Physalia. (See text for further explanation.)

a motion either to the left or to the right of the downwind direction, sufficient to oppose the converging currents, would make it possible for a Portuguese Man-of-war to avoid remaining within a convergent zone. There appeared to be no way in which a Physalia moving to the left across a vortex field (Figure 47A) would pass through fewer convergences than an animal moving to the right.

What might be the effect of the vortices upon the feeding of the Physalia, or upon the distribution of its food?

Langmuir's measurements of ascending rates in the upwelling divergences in fresh water give values (1 to 1.5 cm/sec) which are well in excess of the settling rates of at least one very abundant zooplankton, *Calanus finmarchicus* (Gunnerus), (Gross and Raymont, 1942). In the ocean these rates of ascent in divergences would be greater than in fresh water, under otherwise similar conditions, since salt concentrations due to evaporation should cause a general increase in the rates of vertical motion. Hence it seems probable that the upwelling divergent zones at the sea surface contain plankton carried up from the bottom of the mixed layer. When within the regions of lateral surface flow from the divergences to the convergences, the suspended plankton would have ample time to settle many centimeters below the reach of the Physalia's tentacles before descending in a convergent zone. For the Physalia, this would mean that surface waters would be divided into rich and poor feeding bands extending parallel with the wind, the divergent zone being rich and the convergent zone being poor. However, there still appeared to be no reason why a Physalia moving forty-five degrees to the right of the downwind direction across a field of symmetrical vortices (Figure 47A) would not fare as well as one moving forty-five degrees to the left.

A possible indication of greater advantage from leftward motion seemed to lie in the assumption of an asymmetrical arrangement of the wind-induced parallel vortex pairs, with the larger eddy rotating clockwise (Figure 47A′ & B′). Such an asymmetry would imply an unequal distribution of the forces affecting the circulations. The deflecting force of the earth's rotation (Corioli's force) might supply this inequality.

If Corioli's force is assumed to cause an asymmetry of the wind-induced vortices, and if this asymmetry presents an adequate indirect reason for the leftward motion of the Physalia, it then seemed obvious that a simple first check upon the validity of these assumptions could be made from observations of the Portuguese Man-of-war in the southern hemisphere. If the above assumptions were correct, then in southern latitudes one would expect to find most of the Physalia moving to the right of the wind. This expectation proved to be correct concerning specimens available for examination from the southern hemisphere. Of twenty-two south-latitude animals preserved at the Museum of Comparative Zoology, Harvard University and at the U. S. National Museum in Washington, nineteen were left-handed and three were right-handed. That is, eighty-six per cent of them were mirror images of the majority of the animals from the northern hemisphere, and, as a result, would sail to the right of the wind. This partly-confirmed prediction suggested that the assumptions concerning the effect of Corioli's force upon the vortices might have value in fact.

DRIFT BOTTLE EXPERIMENTS

Some recent drift bottle experiments give further evidence that the assumption of asymmetry in the vortices, based upon deductions drawn from the Physalia movements, may be correct.

During April 1942, some special drift bottle tests were made in the surface waters of the Central Sea area of the Gulf of Mexico (Lat. 27° 30′ N., Long. 86° 40′ W.). One hundred numbered bottles (130 cc displacement 12 cm draft) with hard rubber caps were painted a bright orange color and then ballasted with water so that each bottle had a buoyancy of one gram (± 0.1 gram) in the sea water in which they were used. With this small buoyancy the tops of the bottles floated so near the water surface that the surface film swept across the tops continuously. Thus direct wind drag on the bottles was reduced to a minimum.

Before distributing these drift bottles on the sea surface it was necessary to be free of water disturbances caused by the hull of the research vessel ATLANTIS. For this purpose a twelve foot dinghy was used, but this practice necessarily confined these drift studies to winds below Beaufort 5.

Figure 47A′ gives an example of one orientation of the bottles relative to the wind. The open circles show how the bottles were initially distributed from the small boat. Within three to five minutes all of these bottles were always reformed into new lines parallel with the wind direction (shown by the black circles) and at right angles to the initial line of distribution. From Langmuir's measurements (1938, p. 2), and from later tests made by the author, it has been found that the surface water in the convergences moves downwind more rapidly than the water between them. Hence, one would expect that the bottles which happened to be dropped into the water nearest to the convergences would be the lead bottles in the line (i. e., first at the downwind end of the line). With these bottle numbers as references and with the known numerical order and spacing of the preceding and succeeding bottles as initially distributed, one could observe the number of bottles in any particular convergence which came from the right and left of that line, hence the comparative distances to the two adjacent divergences. For example, bottle number twenty in figure 47A′ (open circles) was dropped in a convergence and became lead bottle in that line. If the helical vortex pairs were perfectly symmetrical, then one would expect to find bottles fifteen to twenty-five in the line, with number twenty leading. If the vortices are asymmetrical, with the clockwise eddy larger, then number twenty would be followed by more numbers less than twenty and fewer numbers greater than twenty. In eighteen series of such drift tests (Table II) made in deep water in the Gulf of Mexico, it was found that an average of six bottles came from the left of the line compared to four from the right. Three of these tests showed a small opposite tendency.

No exact method could be devised to make the bottle spacing equidistant initially. However, by tossing them over rhythmically, about two meters apart, the dinghy being rowed steadily at right angles to the wind direction, it was thought that any errors due to spacing would be random. Table II gives the data relative to these drift bottle tests.

TABLE II—Drift Bottle Tests in the Gulf of Mexico (27° N. 86° W.) in 1942

Test No.	*Date*	*Number and Percentage of bottles originating:*				*Temperatures in (°F)*			*Wind*		*Depth of mixed layer in meters*
	1942	*on left**		*on right**		*Air*		*Water*	*Force*	*Dir. (true)*	
		No.	*%*	*No.*	*%*	*Wet*	*Dry*				
1	Apr. 21	38	46	44	54	67.7	70.9	71.8	2	63°	7
2	Apr. 21	45	58	33	42	67.0	71.1	72.4	2	85	
3	Apr. 22	46	54	39	46	64.2	73.1	75.5	2	25	11
4	Apr. 22	60	74	21	26	64.4	71.6	73.7	3	15	
5	Apr. 22	46	55	38	45	64.4	71.5	73.7	3	25	
6	Apr. 23	61	69	27	31	67.4	71.4	70.5	3	95	9 to 15
7	Apr. 23	60	72	23	28	67.8	71.8	70.6	3	100	
8	Apr. 23	56	69	25	31	67.8	71.8	70.6	3	100	
9	Apr. 23	48	60	32	40	67.6	71.8	70.8	3	100	
10	Apr. 23	36	47	41	53	66.8	71.9	70.9	3–4	95	
11	Apr. 23	49	61	31	39	66.5	72.1	71.0	3	95	
12	Apr. 23	46	60	32	40	66.5	72.1	71.0	3	90	
13	Apr. 25	40	51	39	49	67.7	71.7	70.1	4	105	27
14	Apr. 26	51	63	30	37	67.3	71.5	70.2	3	115	20
15	Apr. 27	41	56	32	44	68.5	72.4	71.4	2.5	105	4
16	Apr. 27	52	71	21	29	68.2	72.2	71.4	2.5	105	
17	Apr. 27	32	44	40	56	68.3	72.2	71.5	2	105	
18	Apr. 27	50	74	18	26	68.7	72.6	71.8	2.5	110	
Average percent			60.2		39.8						

* Facing downwind.

DISCUSSION

Figure 47A gives an idealized drawing of the surface motions in paired symmetrical helical vortices uninfluenced by the deflectional effects of the earth's rotation. Figure 47A′ shows a hypothetical relative directional change of the surface motions under the influence of the deflection effect. The total deflectional displacement of motion in a given vortex pair is probably affected by their unknown subsurface motions. However, the general effect of the surface deflections should be an extension of the axial component of motion in the counterclockwise vortex and a shortening of the axial component in the clockwise vortex. These changes in the axial component should result in a retarding of the rate of cross-wind flow in the left vortex and an increase in the cross-wind flow in the right (clockwise) vortex (Figure 47C′). Thus the clockwise vortex should be larger and the counterclockwise vortex smaller; of course the total energy of motion of each vortex pair would remain the same.

One important result of such a distortion of the surface vortices, as it might affect the feeding of the Physalia, would be the reduction of the speed of cross-wind flow in the counterclockwise vortex and the increase in the speed of cross-wind flow in the clockwise vortex. A decrease in the rate of this cross-wind flow from a point near the divergence to the zero point in the convergence would be important also (Figure 47C′). The average value of the cross-wind flow in this figure is based upon observed rates of drift-bottle convergence, and the slope of the curves seem reasonable in view of the probable cumulative effect of wind-mixing in retarding the surface water while it is moving from the upwelling to the convergence. In such a system of surface flow a Physalia moving to the left would remain, in a given time, within rich waters longer than one moving to the right (Figure 47A′, dashed lines). Also, the Physalia moving to the left would pass through fewer convergent zones, as a consequence of its more extended course diversions between these zones (Figure 47A′, dashed line 1). Thus in the northern hemisphere the Physalia moving to the left should catch more food at less risk of fatal entanglement than one moving to the right.

Hence, it appears that the circulation of surface waters as outlined above would explain the motions of the drift bottles as well as the proponderance of motion of the Physalia to the left of the downwind direction.[2] Further drift bottle tests should soon give conclusive data concerning the reliability of the results obtained from these first, rather crude, exploratory tests. Plankton net tows in convergent and divergent zones should readily show the effects of the helical vortices upon plankton population distribution in surface waters. Also, further observations of Physalia north and south of the equator may enlarge upon the biological implications of this apparent reversal of asymmetry with hemisphere.

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[2] Large numbers of *Vellela* were recently seen in the Gulf of Mexico. Of hundreds of animals observed, all were sailing to the left of the downwind direction. This seems to indicate that the factors which produce the leftward motion under the influence of the wind are not confined to the Physalia alone.

SUMMARY

Observations are given which show a curious tendency of the pneumatophore of the Portuguese Man-of-war (*Physalia pelagica*) to be so oriented with the wind as to cause the animal to be driven about forty-five degrees to the left of the downwind direction. These observations were made over a large part of the North Atlantic and Gulf of Mexico during a period of about three years.

A hypothesis advanced to explain this leftward tendency required in part that: (a) southern hemisphere *Physalia* be mirror images of those in the northern hemisphere, and that they sail to the right of the downwind direction: (b) wind-induced helical vortex pairs be set up in surface waters at sea, and that these vortices be asymmetrical.

Of twenty-two Physalia from the southern hemisphere available for examination in museum collections, nineteen (86%) were mirror images of those in the northern hemisphere and would sail to the right of the wind.

Drift bottle tests on the open sea have shown that lines of convergence are set up by the wind which are oriented parallel with the wind direction. These lines apparently mark the surface convergences of parallel left and right helical vortex pairs set up by the wind. The tests suggest that these vortices were asymmetrical, the larger vortex of each pair rotating clockwise, the smaller counterclockwise (facing downwind). This asymmetry was shown by the larger number of bottles drifting into the average convergence from the left of that line, the initial distribution of the drift bottles having been approximately equidistant in a line at right angles to the convergence lines.

Such an asymmetry would imply an unequal distribution of the forces driving the circulations. The deflecting force of the earth's rotation may supply this inequality. Hence the following theory is proposed: Corioli's force and frictional forces may produce an asymmetry in the wind-induced helical vortex pairs developed in surface waters on the open sea.

Four facts are apparent: first, the widespread prevalence of the leftward motion (in the given areas) of the animals; second, the reversal of asymmetry among *Physalia* of the southern hemisphere; third, the formation of lines of convergence in the surface water of the open sea parallel with the wind direction; fourth, the six to four average relationship between the number of drift bottles which came

from the left of the surface convergences as compared to those coming from the right of the convergences. While the eighteen drift tests recorded in Table II do not conclusively prove an asymmetry in the helical vortex as developed in the surface waters of the deep sea, they are highly suggestive that such asymmetry exists. Further drift bottle tests and other experiments are planned, but in view of the inherent uncertainties of these times it seems wise to publish these results now.

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AN ANNOTATED CHECK-LIST OF THE SALT-WATER BRYOZOA OF LONG ISLAND SOUND

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Contribution from the Woods Hole Oceanographic Institution, Number 332

I. INTRODUCTION

No definitive treatment exists for the Bryozoa of Long Island Sound. What few published records there are occur as incidental information in general discussions of other regions; of these, the chief sources are Verrill's data in Verrill and Smith (1873), and occasional references by Osburn (1912). This condition is, of course, part of the general relative paucity of information about the Sound. The United States Fish Commission's work of 1874 proved an abortive start, as interest and emphasis rapidly shifted to other areas, and it is only in the last quindecennium that maintained serious investigation has developed due to the extensive interests of the oyster fishery. This recent research, which already has yielded many fundamental data, has been prosecuted directly or indirectly largely through the agency of the Milford Laboratory of the present Fish and Wildlife Service. To that institution, in the persons of Dr. Victor Loosanoff and Mr. James Engle, I am myself indebted for much assistance, the use of the laboratory, and opportunities to make collections on the oyster grounds during 1939 and 1940. Economic considerations of the oyster fishery may be expected eventually to necessitate a thorough quantitative study of the bryozoan populations of the oyster grounds, and for this reason, in addition to general academic interest, it has seemed worth while to summarize the available qualitative information about the group in Long Island Sound waters.

It is a particular pleasure to dedicate this work to Professor Alexander Petrunkevitch. No small part of this pleasure derives from the fact that he was the first to introduce me to that perplexing, but infinitely intriguing group, the Bryozoa. In more than one sense this contribution is the direct result of the encouragement he offered my early interest, for the records from my own collections were compiled almost entirely during my student days with him. For these reasons this summary of the Long Island Sound data has seemed especially appropriate to the occasion; it is offered in this sense, with mingled feelings of affection and gratitude. L.W.H.

II. MATERIALS AND METHODS

The check-list includes all species for which specimens are definitely known from Long Island Sound, and, in addition, all the known published records for these and other species. The names of species which are known only from published records, and about which there is some question, either on the grounds of determination or locality, are enclosed in square brackets.

From my own collections made between 1937 and 1940 from Bridgeport to Clinton, and at Mt. Sinai, Long Island, twenty-seven species could be reported. These records were included in an unpublished doctoral dissertation submitted to the Faculty of the Graduate School of Yale University in 1941. Of particular importance are the records from Clinton harbor and from the Milford Laboratory oyster ground stations numbered here M-1 to M-15, all of which were redredged a number of times. The numbers of these M stations are those used by that laboratory during the period of my investigations. Also included here are records from four dredgings, as follows: A, from M-7 to M-8; B, M-6 to M-7; C, M-3 to M-6; and D, M-7 to M-8. Besides these samples, collections were made along shore at several places. Finally, I have recently examined some samples from a navigation buoy at Execution Rocks, in the extreme western end of the Sound, and these records, too, are incorporated here. All such records from my own collections are given first and identified by the symbol (LWH).

In 1941-42 Dr. Raymond C. Osburn and I undertook the study of the Atlantic Coast Bryozoa. Dr. Albert Parr and Dr. Stanley Ball of the Yale University Peabody Museum, and Dr. Elisabeth Deichmann of the Harvard University Museum of Comparative Zoology kindly loaned us the material from the respective museums. I have included here the data from 27 lots of material in the Yale collections and one from Harvard which apply to Long Island Sound. Since most of these collections were unsorted and unidentified they bore no accession numbers; to designate the many lots we found it expedient to assign each a number carrying the symbols YPM and MCZ respectively. These numbers were left in the collections, and I have retained them here. I have also included records from Dr. Osburn's collection, designated (RCO). The bulk of the pertinent YPM and RCO material was from the 1874 Fish Commission collections, made by Verrill. The data accompanying the samples were most inadequate—even station numbers were lacking—but there was generally some statement such as "Fishers Island Sound" or "Off Noank" which permitted rough location of the source. Samples labeled "Long Island Sound" are probably from the numbered stations shown in Figure 1 in the eastern part of the Sound. Some additional dredgings were made by the *Fish Hawk* in 1890, and certainly one sample, that from Point-No-Point (RCO), is from this series. These various sources, together with published records, raise the total number of species to 42 which are certain and 5 more which are dubious. Figure 1 shows all the localities mentioned, except Sea Flower Reef which is in Fishers Island Sound.

From the foregoing remarks some estimate may be made of my indebtedness to Dr. Osburn. His generous interest in my work has been unfailing, and our association at the Ohio State University during my 13 months tenure of a Mary S. Muellhaupt Scholarship, when many of these records were worked out, was most happy. In particular I must acknowledge his gift of many specimens and the liberal sharing of his records.

In listing the species I have followed closely the groupings accepted by Osburn (1933, 1940) in his recent works. His report on the Woods Hole area (1912) contains adequate descriptions, keys, figures, and earlier synonyms for all but one of the forms, but the nomenclature, like that of the Chesapeake Bay paper (1932), should be corrected by reference to the two more recent.

The term *soft substrates* has reference to algae, hydroid stems, and similar habitats; *hard substrates* include shells and stones.

III. VERIFIED AND ALLEGED RECORDS

PHYLUM BRYOZOA Ehrenberg, 1831

Subphylum Endoprocta Nitsche, 1869

Order PEDICELLINEAE Hincks, 1880

Family PEDICELLINIDAE Johnston, 1847

Genus Pedicellina M. Sars, 1835

Pedicellina cernua (Pallas), 1771. On hard substrates at M-1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15; Double Beach (LWH).

Verrill (1873), as *P. americana* Leidy: "New Haven, Connecticut, to Vineyard Sound."

Genus Barentsia Hincks, 1880

Barentsia discreta (Busk), 1886. On hard substrates at M-4, 6, and 15 (LWH).

Barentsia major Hincks, 1888. On hard substrates at M-2, 3, 4, 5, 6, 7, 9, 10, 11, 15 (LWH). Long Island Sound (YPM 208).

Subphylum Ectoprocta Nitsche, 1869

Class GYMNOLAEMATA Allman, 1856

Order CYCLOSTOMATA Busk, 1852

Family CRISIIDAE Johnston, 1847

Genus Crisia Lamouroux, 1812

Crisia eburnea (Linnaeus), 1758. On soft substrates at Pine Orchard and lower Clinton harbor (LWH). Stonington (YPM 269); Noank (YPM 203); Thimble Islands (YPM 212, RCO); New Haven (YPM 216); Long Island Sound (YPM 209, 415). Verrill (1873): "common near New Haven, and at Thimble Islands, 1 to 6 fathoms, rocky, and in tide pools."

Family TUBULIPORIDAE Johnston, 1838

Genus Tubulipora Lamarck, 1816

Tubulipora liliacea (Pallas), 1766. Fishers Island Sound (YPM 202); Sea Flower Reef (RCO); Noank (YPM 203); New Haven (YPM 216). Verrill (1873), as *T. flabellaris* Smitt,: Thimble Islands on algae and hydroids. Cf. Osburn (1912) for synonymy.

[*Tubulipora flabellaris* (Fabricius), 1780.] Osburn (1935): "Long Island Sound to Greenland." I can find no substantiated records west of Vineyard Sound; the listing may be an error from Verrill's misuse of the name for the preceding species, q. v.

Family LICHENOPORIDAE Hincks, 1880

Genus Lichenopora DeFrance, 1823

Lichenopora verrucaria (Fabricius), 1780. Verrill (1873), as *Diastopora patina* Smitt,: "Near New Haven, at Thimble Islands, 1 to 5 fathoms." Osburn (1935): "South to Long Island Sound." Probably on soft substrates only.

Order CTENOSTOMATA Busk, 1852

Group A. Carnosa Gray, 1848

Family ALCYONIDIIDAE Hincks, 1880

Genus Alcyonidium Lamouroux, 1821

[*Alcyonidium hirsutum* (Fleming), 1828.] Osburn (1935): "Long Island Sound to the Arctic Ocean." I can find no more certain references. Specimens so labeled in the Verrill collections proved to be *Flustrella hispida* (from New Haven, YPM 217) and *A. polyoum* (from Savin Rock, RCO). This casts serious doubt on Verrill's (1873) records: "Savin Rock, near New Haven; . . . Thimble Islands."

Alcyonidium parasiticum (Fleming), 1828. Fishers Island Sound (YPM 202).

Alcyonidium polyoum (Hassall), 1841. On hard and soft substrates abundant at M-2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15; Clinton lower harbor; Double Beach (LWH). Stonington (YPM 204, 406); Thimble Islands (YPM 359); Savin Rock (RCO); Long Island Sound (YPM 205, RCO). Verrill (1879a), the red variation as *A. rubrum* n. sp.,: Long Island Sound. Osburn (1935): Long Island Sound.

Alcyonidium verrilli Osburn, 1912. Momauguin (LWH). Thimble Islands (YPM 210, 403, RCO); New Haven (YPM 216); Long Island Sound (YPM 214). Verrill (1872), as *A. ramosum* n. sp.,: New Haven; (1873): New Haven and Thimble Islands; (1879b): New Haven. Osburn (1912): Long Island Sound. The name *ramosum* was preoccupied, and Osburn (1912) renamed the species in Verrill's honor. New Haven may be taken as the type locality.

Family FLUSTRELLIDAE Hincks, 1880

Genus Flustrella Gray, 1848

Flustrella hispida (Fabricius), 1780. On *Fucus* at Double Beach (LWH). Thimble Islands (YPM 210, RCO); New Haven

(YPM 217, RCO). Verrill (1873): Savin Rock and Thimble Islands. Osburn (1935): Long Island Sound.

Group B. PALUDICELLEA Allman, 1856

Family NOLELLIDAE Harmer, 1915

Genus ANGUINELLA Van Beneden, 1844

Anguinella palmata Van Beneden, 1844. Thimble Islands (YPM 214); New Haven (YPM 216).

Group C. VESICULARINA Johnston, 1847

Family VESICULARIIDAE Johnston, 1838

Genus AMATHIA Lamouroux, 1812

Amathia vidovici (Heller), 1867. Station M-10 (LWH). Noank (RCO); Thimble Islands (RCO); Long Island Sound (YPM 208, 209). Verrill (1873), as *Vesicularia dichotoma* n. sp.,: Savin Rock, off New Haven Light, Thimble Islands, Norwalk. The last record presumably refers to the adjacent coast at South Norwalk. Generally on hard substrates.

Genus BOWERBANKIA Farre, 1837

Bowerbankia gracilis Leidy, 1855. On hard and soft substrates. M-1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15; Milford; Double Beach; Clinton lower harbor; Hammonasset River about 1 mile above U. S. Highway 1 bridge; Execution Rocks (LWH). Noank (YPM 203); Thimble Islands (YPM 210, 212, 213, 214); New Haven (YPM 216, 218). Verrill (1873), the nominal variety *caudata* as *Vesicularia fusca* Smitt,: South End, near New Haven. Osburn (1912): Long Island Sound.

Group D. STOLONIFERA Ehlers, 1876

Family BUSKIIDAE Hincks, 1880

Genus BUSKIA Alder, 1856

Buskia armata (Verrill), 1873. Dredge D; M-10; Pine Orchard; Execution Rocks (LWH). New Haven (YPM 216, 219); Long Island Sound (YPM 208, 209). Generally on soft substrates.

Buskia setigera Hincks, 1877. Pine Orchard (LWH). In listing this as a separate species I have followed Osburn (1940).

Family TRITICELLIDAE G. O. Sars, 1873

Genus Triticella G. O. Sars, 1873

Triticella elongata (Osburn), 1912. Execution Rocks, on *Tubularia crocea* (LWH). Verrill (1873) may have referred to this species in his records for *Farrella familiaris* from the Thimble Islands; if not, these records cannot be assigned elsewhere.

Order CHEILOSTOMATA Busk, 1852

Suborder ANASCA Levinsen, 1909

Division I. Inovicellata Jullien, 1888

Family AETEIDAE Smitt, 1867

Genus Aetea Lamouroux, 1812

Aetea anguina (Linnaeus), 1758. Stonington (YPM 204); Thimble Islands (YPM 212); New Haven (YPM 216); Long Island Sound (YPM 208, 415). Verrill (1873): off New Haven. Osburn (1935): Long Island Sound.

Division II. Malacostega Levinsen, 1909

Family MEMBRANIPORIDAE Busk, 1854

Genus Conopeum Gray, 1848

Conopeum reticulum (Linnaeus), 1767. On hard substrates and eel-grass. M-1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14; throughout Clinton harbor; Hammonasset River 1 mile above U. S. Highway 1 bridge; Execution Rocks (LWH). New Haven (YPM 215).

Genus Acanthodesia Canu and Bassler, 1920

Acanthodesia tenuis (Desor), 1848. Common on hard substrates. Dredges A, B, C; M-1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15; lower Clinton harbor; Double Beach; Pine Orchard; Milford (LWH). Point-No-Point (RCO); Long Island Sound (YPM 209, RCO). Verrill (1873), as *Membranipora tenuis* Desor,: near New Haven.

Family ELECTRINIDAE D'Orbigny, 1851

Genus Electra Lamouroux, 1816

Electra pilosa (Linnaeus), 1767. Typically on soft substrates, specially *Laminaria* and *Ulva.* Dredge A; M-10; lower Clinton harbor; Pine Orchard; Momauguin; Milford (LWH). Stonington (YPM 204, 269, 410); Noank (YPM 203, RCO); Long Island Sound (YPM 206, 209, RCO). Verrill (1873), as *Membranipora pilosa* Farre,: Savin Rock, New Haven, and Thimble Islands. Osburn (1935): Long Island Sound. Specimens from Noank (RCO) labeled by Verrill as *Memb. americana* are the short-spined form of this species.

Electra hastingsae Marcus, 1938. On hard substrates. Stations M-3, 5, 6, 7, 9, 10, 13, 15; lower Clinton harbor (LWH). Long Island Sound (YPM 208, 209, RCO). Osburn (1912), cf. *Membranipora monostachys,* believed Verrill's (1873) records for *Membranipora lineata* Busk from New Haven and elsewhere apply properly to the present species.

Family ALDERINIDAE Canu and Bassler, 1927

Genus Callopora Gray, 1848

Callopora aurita (Hincks), 1877. On hard and soft substrates. Dredges A, C; M-4, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15; lower Clinton harbor; Pine Orchard; Mt. Sinai (LWH). Stonington (RCO); Long Island Sound (YPM 208, RCO). The Stonington specimens were labeled by Verrill *M.* (embranipora) *unicornis* var. *americana.*

Callopora craticula (Alder), 1857. On hard substrates. Dredge A; M-8, 15 (LWH). Verrill's (1873) records for *Membranipora lineata* Busk may belong here.

[*Callopora lineata* (Linnaeus), 1768.] Verrill's (1873) records of *Membranipora lineata* Busk, properly a synonym of this species, almost certainly are based on misidentification. He notes it as "common near New Haven, from low-water mark to 6 fathoms, on stones, oysters, algae, etc." Osburn (1912) assigns them to *Electra hastingsae*, but since the calloporids are quite different from the electrinids in possessing avicularia and ovicells, it is possible the records really refer to *Callopora craticula*.

Genus TEGELLA Levinsen, 1909.

Tegella unicornis (Fleming), 1828. Long Island Sound, on elasmobranch egg case (RCO). Specimens from Stonington (RCO) labeled by Verrill as his variety *americana*, synonymous with the variety *armifera* Hincks, proved to be *Callopora aurita*.

Division V. CELLULARINA Smitt, 1867

Family SCRUPOCELLARIIDAE Levinsen, 1909

Genus TRICELLARIA Fleming, 1828

Tricellaria ternata (Solander), 1786. Stonington (YPM 269).

Family BICELLARIELLIDAE Levinsen, 1909

Genus BICELLARIELLA Levinsen, 1909

Bicellariella ciliata (Linnaeus), 1758. Stonington (YPM 204); Noank (RCO); Long Island Sound (RCO).

Family BUGULIDAE Gray, 1848

Genus BUGULA Oken, 1815

[*Bugula avicularia* (Linnaeus), 1758.] Verrill (1879a, 1879c): "from Long I. Sound to Spitzbergen." Occurrence within the Sound is dubious but not impossible.

Bugula flabellata (J. V. Thompson), 1847. Stonington (RCO); Noank (YPM 561). Verrill (1879a, 1879c): "*Bugula flustroides* (Lamx.) (= *B. flabellata* Gray). Long I. Sd. to Maine."

Bugula gracilis var. *uncinata* Hincks, 1880. New Haven (YPM 216).

Bugula turrita (Desor), 1848. Hard and soft substrates. M-10 (LWH). Stonington (YPM 204, 410); Noank (YPM 551); Fishers Island Sound (YPM 202, RCO); Thimble Islands (YPM 212, 214, RCO); New Haven (YPM 216); Cold Spring Harbor (MCZ 69); Long Island Sound (YPM 415, RCO). Perkins (1869): New Haven. Verrill (1873): Long Island Sound.

Genus DENDROBEANIA Levinsen, 1909

[*Dendrobeania murrayana* (Johnston), 1847.] Verrill (1879a, 1879c), as *Bugula murrayana*,: "Long I. Sd. to Europe." The occurrence of this species within the Sound is doubtful.

Division VI. CRIBRIMORPHA Harmer, 1926

Family CRIBRILINIDAE Hincks, 1880

Genus CRIBRILINA Gray, 1848

Cribrilina punctata (Hassall), 1842. On hard substrates. Dredges A, B; M-2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 15; lower Clinton harbor; Pine Orchard; Mt. Sinai (LWH). New Haven (YPM 219).

Suborder ASCOPHORA Levinsen, 1909

Family HIPPOTHOIDAE Levinsen, 1909

Genus HIPPOTHOA Lamouroux, 1812

Hippothoa hyalina (Linnaeus), 1767. On hard and soft substrates. M-10; lower Clinton harbor; Pine Orchard (LWH). Stonington (YPM 269, 410); Noank (YPM 203); Thimble Islands (YPM 359); New Haven (YPM 216); Long Island Sound (YPM 209, RCO). Verrill (1873), as *Mollia hyalina* Smitt,: New Haven and Thimble Islands. Osburn (1935): Long Island Sound.

Family SCHIZOPORELLIDAE Bassler, 1935

Subfamily SCHIZOPORELLINAE Canu and Bassler, 1917

Genus SCHIZOPORELLA Hincks, 1877

Schizoporella unicornis (Johnston), 1847. On hard substrates. Dredges A, B; M-1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15; lower Clinton harbor; Milford (LWH). Thimble Islands (YPM 210); New Haven (YPM 216); Point-No-Point (RCO); Long Island Sound (YPM 208, 209, 415, RCO). Verrill (1873), as *Escharella variabilis*,: Long Island Sound.

Genus STEPHANOSELLA Canu and Bassler, 1917

Stephanosella biaperta (Michelin), 1841-42. On hard substrates. Dredge A; M-4, 7, 10, 15; Pine Orchard (LWH). Stonington

(YPM 269); Noank (YPM 203, RCO); New Haven (YPM 216); Long Island Sound (YPM 208, RCO).

Subfamily HIPPOPORININAE Canu and Bassler, 1917

Genus Hippoporina Neviani, 1895

Hippoporina contracta (Waters), 1899. Stonington (YPM 269); Noank (YPM 203); Long Island Sound (RCO). Osburn (1912), as *Lepralia serrata* n. sp.,: Long Island Sound.

Genus Hippodiplosia Canu, 1916

Hippodiplosia pertusa (Esper), 1794-97. Dredge A (LWH). Stonington (YPM 204); Noank (YPM 203); Long Island Sound (YPM 208, RCO). Verrill (1879a), as *Escharina porosa* n. sp.,: Long Island Sound.

Hippodiplosia americana (Verrill), 1875. Noank (YPM 203); Fishers Island Sound (YPM 202); Long Island Sound (RCO). Verrill so confused this and the following species that, as Osburn (1912) has pointed out, "it is . . . impossible to quote Verrill in regard to the range." Osburn (1912): Long Island Sound.

Genus Cryptosula Canu and Bassler, 1925

Cryptosula pallasiana (Moll), 1803. On hard and soft substrates. Dredges A, B, C; M-1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 15; lower Clinton harbor; Pine Orchard; Double Beach; Milford (LWH). Stonington (YPM 269); Noank (YPM 343, RCO); Fishers Island Sound (YPM 202); Thimble Islands (YPM 359); New Haven (YPM 216); Point-No-Point (RCO); Long Island Sound (RCO). Osburn (1912): Long Island Sound.

Subfamily MICROPORELLINAE Canu and Bassler, 1917

Genus Microporella Hincks, 1877

Microporella ciliata (Linnaeus), 1758. Dredges A, B; M-1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15; Pine Orchard (LWH). Stonington (YPM 269); Noank (YPM 203); Thimble Islands (YPM 212); Long Island Sound (RCO).

Family SMITTINIDAE Levinsen, 1909

Genus Smittina Norman, 1903

Smittina trispinosa var. *nitida* (Verrill), 1875. On hard substrates. M-4, 11 (LWH). Stonington (YPM 204); Noank (YPM 203); New Haven (YPM 216); Long Island Sound (RCO). Verrill (1879a), as *Mucronella nitida* Verrill,: Long Island Sound. Osburn (1912): Long Island Sound.

Genus Porella Gray, 1848

Porella acutirostris Smitt, 1867. Long Island Sound (RCO).

Genus Mucronella Hincks, 1880

Mucronella immersa (Fleming), 1847. Long Island Sound (RCO). Verrill (1873), as (?) *Discopora coccinea* Smitt,: "Long Island Sound, northward." Osburn (1935): Long Island Sound.

Family CELLEPORIDAE Busk, 1852

Genus Schizmopora MacGillivray, 1888

Schizmopora americana (Osburn), 1912. Pine Orchard (LWH). Stonington (YPM 269); Noank (YPM 203, RCO); Fishers Island Sound (YPM 202, RCO); New Haven (YPM 216, 218); Long Island Sound (YPM 206, 415). Verrill (1873), as *Cellepora ramulosa* Linné,: New Haven, off South End, Thimble Islands, Faulkners Island. Osburn (1935): Long Island Sound. The species is probably identical with *S. avicularis* (Hincks).

IV. GENERAL NOTES ON THE FAUNA AND ITS DISTRIBUTION

The 42 definite species and 5 dubious ones in this list may be compared instructively with the faunas reported by Osburn for Woods Hole (1912) and Chesapeake Bay (1932). The Woods Hole list comprised 81 species, and included all the forms now known from Long Island Sound except *Buskia setigera.* Of the 81, however, 28 were found only in the colder off-shore waters. Four of these cold water species occur in Long Island Sound: *Tricellaria ternata, Tegella unicornis, Porella acutirostris,* and *Alcyonidium parasiticum*; two more are in the doubtful list: *Tubulipora flabellaris* and *Dendrobeania murrayana.* The chief distinction between the two faunas thus lies in the absence from Long Island Sound of a number of northern species which reach their southern limit in the vicinity of Nantucket Shoals. The 42 Long Island Sound forms might better be compared to the 53 in-shore plus 4 off-shore species of Woods Hole, and this discrepancy is less than one could expect, particularly since several of the species missing from the Sound are rare or uncertainly recorded from Woods Hole. Of the 12 species which Osburn found only in the in-shore waters, all have been found in the Sound except the endoprocts *Loxosoma davenporti* and *L. minuta*, both commensal on worms, and for these no special search seems to have been made. When all these qualifications are considered, the Long Island Sound and in-shore Woods Hole lists have a similarity amounting to virtual identity.

Only 19 species were reported by Cowles (1930) and Osburn (1932) from Chesapeake Bay, but this small number as well as the disproportionate ctenostome representation is due in part to the limitations of collecting, both in methods and habitats. Three of these do not occur in Long Island Sound: *Amathia alternata, Victorella pavida,* and *Membranipora membranacea.* The two areas have in common *Barentsia discreta, Crisia eburnea, Alcyonidium parasiticum, A. polyoum, A. verrilli, Anguinella palmata, Bowerbankia gracilis, Triticella elongata, Acanthodesia tenuis, Electra pilosa, E. hastingsae, Bugula turrita, B. gracilis uncinata, Hippothoa hyalina, Schizoporella unicornis,* and *Microporella ciliata.* The majority of the Chesapeake species occurred at the lower end of the Bay, but *Acanthodesia tenuis, Alcyonidium verrilli,* and *Bowerbankia gracilis* penetrated to salinities as low as 13 to 15 per mille, and *Membranipora membranacea* to 10. The most notable difference between this fauna and that of Long Island Sound is due to the presence in the latter of a number of more or less sub-arctic encrusting species; the species common to both are in general widely distributed along the Atlantic Coast, though *Alcyonidium verrilli* and *Anguinella palmata* appear to be restricted to moderately brackish localities. A truer comparison will be possible when the Chesapeake oyster grounds are studied.

The distribution of species in Long Island Sound is reminiscent of the situation in Chesapeake Bay in that the richest fauna is found in the eastern, open end. The four definite species of the Woods Hole off-shore waters all occur in that vicinity. In addition, all the records for *Tubulipora liliacea, Bicellariella ciliata, Bugula flabellata, Hippoporina contracta, Hippodiplosia americana,* and *Mucronella immersa* probably apply only to the region east of the Connecticut River. The greater number of species in this region need occasion no surprise. In the first place it is immediately adjacent to the passages into Block Island Sound, and hence is most readily accessible for colonization by immigrant species. In addition, it is the region of highest salinity according to the figures of Galtsoff and Loosanoff (1939) and Loosanoff and Engle (1940), who state that the salinity of the bottom water increases eastward from values of about 25 to 26 at the western extreme to 30 or 32 in Fishers Island Sound. Thirdly, if any temperature gradient exists, the colder water may be expected at the eastern end; adequate data to establish this do not seem to be available in published form, but it is reasonable to suppose that the intruding sea water responsible for the higher salinities is also colder than the water of the shallow Long Island Sound basin.

The lack of requisite data for the collections from the eastern region unfortunately limits any discussion of general distribution. Some further analysis is possible, however, of the distribution on the oyster grounds between Bridgeport and Momauguin, and at Clinton, a matter of major interest. Heavy populations of bryozoans on the oyster grounds probably have at least two adverse effects on the oyster population: 1) the amount of substrate available for the oyster set is severely reduced, and 2) great numbers of oyster larvae presumably are eaten prior to attachment. Evidence on these points for some other sessile groups, including hydroids, has been discussed by Orton (1937), while Dr. Osburn (in litt.), on the basis of recent studies in Chesapeake Bay, concludes that the bryozoa are indeed detrimental to the oyster beds. I have made no direct studies of this problem, but my impression of the Long Island Sound situation would accord well with such views; in some of the dredgings nearly every shell and piece of substrate was almost solidly encrusted, while throughout the beds examined bryozoa were extremely abundant.

From point of view of their prevalence, the species of the oyster beds fell easily into two groups: 1) those found at five or fewer stations, the rare or occasional forms; and 2) the basic fauna of 12 species taken at nine or more stations. The latter were *Pedicellina cernua, Barentsia major, Alcyonidium polyoum, Bowerbankia gra-*

cilis, *Acanthodesia tenuis*, *Conopeum reticulum*, *Electra hastingsae*, *Callopora aurita*, *Cribrilina punctata*, *Schizoporella unicornis*, *Cryptosula pallasiana*, and *Microporella ciliata*. The distribution of these 12 species was peculiar in one respect. At most of the stations from 10 to all 12 were present; on the oyster grounds in lower Clinton harbor, however, as well as at the stations within the breakwater limits of Bridgeport harbor (M-1) and New Haven harbor (M-12, 13, 14), only 6 or 8 of these species were found. Curiously the distinction concerns the number of species only, for different ones were lacking in each case. The extensive data of the Milford Laboratory, as well as my own observations, show that the very slight differences in salinity, temperature, and pH are wholly inadequate to explain this; the maximum salinity differences between stations are only 1 or 2 per mille, for example, and the values for Clinton harbor are as high as those for any of the offshore members of the M series. In short, there is no satisfactory interpretation of the phenomenon at present. The explanation may well prove a complex one of population statistics, for it is difficult to envisage a single factor acting causally to limit just the number of species.

If the distribution on the oyster grounds as a whole must remain mysterious, however, the distribution within Clinton harbor presents intelligible points of interest. As can be seen on the map, the harbor is sharply divided into an upper and a lower part; throughout both the bottom is paved with oysters, and some parts are commercially cultivated. In the upper harbor only the channel is of interest here, since the flats filling the remainder are often exposed. The lower harbor was found to support a typical harbor bryozoan population of eight of the dominant species, and an additional three which were limited to algae and soft substrates. Six of the eight dominants were found also in the extreme lower part of the upper harbor, but five of these suddenly dropped out and the great majority of the upper harbor channel was colonized solely by large numbers of *Conopeum reticulum*. This species, and also *Bowerbankia gracilis*, were taken even well up into the Hammonasset River. Extensive studies over two years established the fact that the point of sudden change in the population coincided almost exactly with the site at which diurnal tidal salinity variations were first detectable. The entire upper harbor has a nearly uniform bottom salinity at high tide, ranging during long periods of time from about 26 to nearly 29. The lower end of the upper harbor shows no appreciable difference at low tide, but at the extreme upper end the low tide values are often below 20, and still lower values, of course, are found in the river.

It seems clear that salinity is the controlling factor in this instance. The limiting values, however, appear rather high, for even at the upper end of the harbor the average salinity was apparently about 23, and where the faunal change occurred the figure would be higher still. This may be compared with Osburn's figure of 13 as the limit for *Acanthodesia tenuis* in Chesapeake Bay, a species also involved in the present case. One plausible interpretation lies in the fact that the Chesapeake Bay bottom water is possibly quite constant, with the salinity showing only seasonal or other long phase variations, whereas the salinity of Clinton harbor water fluctuates continually with the tides. To adapt Parr's (1933) useful temperature terminology, a given station in Chesapeake Bay could be characterized as homostenohaline, and one in upper Clinton harbor as heteroeuryhaline. Such distinctions appear to be valid in temperature considerations, and it would be logical to extend them to salinity and other factors. In all probability the critical tolerances of environmental variations are those of the larvae, particularly during metamorphosis when they may be supposed to be minimal. In this connection it may be noted that some colonies of *Alcyonidium polyoum*, *Acanthodesia tenuis*, and *Electra hastingsae* incidentally transplanted from the lower harbor region to a point in the river where variation was quite extreme survived and grew during two weeks about as well as colonies of *Conopeum reticulum* similarly treated, indicating that the conditions were not too extreme for the adults of these species.

A final point concerns the sudden abundance of *Conopeum reticulum* in the upper harbor. While quantitative studies did not fall within the scope of these investigations, general observation suggested that the magnitude of this abundance was perhaps ten times greater than at any other region within the oyster grounds. It is reasonable to suppose this reflects the lack of competition by the other species for the available substrate. Should further research prove this to be true, it would indicate that the total number of colonies of the common encrusting species may depend chiefly on the amount of substrate, irrespective of the number of species. The problem and its collateral question of possible relationships between amounts of substrate and the percentage encrustation deserve investigation, particularly in view of the common practice of distributing large quantities of fresh shell over the cultivated oyster grounds; the efficiency of this operation may involve more delicate considerations than have been generally supposed.

V. SUMMARY

1. The Bryozoan fauna of Long Island Sound comprises 42 certain species and 5 more which are doubtfully recorded.
2. The Long Island Sound fauna is almost identical with that of the in-shore waters of Woods Hole, and has many species in common with that of Chesapeake Bay.
3. The greatest number of species occur in the eastern end of the Sound; this region is most accessible to immigrant forms, and is more saline and probably colder than the inner parts of the Sound.
4. The oyster grounds of the Connecticut coast are populated by a basic group of 12 common species. At the stations along the shore from 10 to 12 of these are present, but in the harbors the number of species falls to 6 or 8; this phenomenon is not understood at present.
5. In Clinton harbor most species do not penetrate beyond the point at which diurnal tidal salinity variations appear. Such variations, even where the values concerned are high, seem to be as effective in limiting distribution as do maintained low values. There is some evidence to support the presumption that the critical tolerances are those of the larvae.

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Contribution No. 333

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NEW SHARKS FROM THE WESTERN NORTH ATLANTIC[1]

BY HENRY B. BIGELOW AND WILLIAM C. SCHROEDER[2]

Genus APRISTURUS Garman, 1913

THESE little sharks, of deep water, are known from very few specimens, but the named 'species' (thirteen in number, from widely separated seas) appear separable by sufficiently precise differences, though they resemble one another closely. Fowler[3] has even distributed them among three subgenera (Parapristurus, Pentanchus, and Apristurus), according to the degree of cirrus-like development of the margins of the nostrils. But the differences in this respect are not sharp enough for generic separation. The several species do, however, fall into two sharply contrasting groups, as regards the gill openings, for while, in the one group, typified by *A. brunneus* Gilbert, 1891, from the west coast of North America, these are of the ordinary type, in other species they are close together above and below, but so deeply concave anteriorly, at the mid-level, that the tips of the gill filaments are exposed. It is astonishing that attention has not been called earlier to this, for the gills are clearly pictured thus in *A. atlanticus* Koefoed,[1] as well as in *A. microps* Gilchrist, 1922,[2] and reëxamination of the type specimen in the U. S. National Museum, shows them to be of this same type in *A. profundorum* Goode and Bean, 1895, and in *A. verweyi* and *A. herklotsi* Fowler, 1934,[3] although no suggestion of the fact appears in original accounts or illustration of these species. Under ordinary circumstances, a difference so striking would demand the institution of a new genus. In the present case, however, such action does not seem advisable, because neither the account nor the illustration of the type species of Apristurus,[4] gives any definite information as to its gill openings; hence there is no way of knowing to which subdivision of the old genus Apristurus it actually belongs; neither are the specimens available for study at present, being presumably in Berlin. It therefore seems wise to use the name Apristurus in the more inclusive sense for the time being.

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[1] Published with the aid of a grant from the Museum of Comparative Zoölogy at Harvard College.

[2] Contribution, no. 333, of the Woods Hole Oceanographic Institution.

[3] 1941, Bull. 100, U. S. Nat. Mus. **13**, p. 53.

Up to date, three species have been named from the North Atlantic, *profundorum* Goode and Beane, 1895, from the offing of Delaware Bay; *atlanticus* Koefoed, 1932, from the eastern North Atlantic; and *laurussoni* Saemundsson, 1922, from Iceland. In all three of these the second dorsal is little, if any, larger in area than the first, and the first and second gill openings are only about half as long as the distance between the nostrils. In a specimen taken off the north coast of Cuba, however, by the research ship 'Atlantis' in March, 1938, the gill openings are nearly or quite twice as long as this, relatively, and the second dorsal is about twice as large in area as the first. It differs further from the type specimen of *profundorum* (with which we have compared it) in a much longer caudal (about one third of total length, as against only about one fourth of total length in *profundorum*), also in the fact that its anal is noticeably different in shape (*cf.* pl. VII with fig. 1). Neither can it be referred to the South African *soldhana* Barnard, 1925, the interspace between its two dorsal fins being relatively much shorter, nor to *microps* Gilchrist, 1922 (also from South Africa), its gill openings being much larger relatively than those of the latter, the interspace between its pectorals and pelvics much longer, and that between its first and second dorsals also considerably longer, relative to the length of the snout. It also differs in various respects from the several 'species' that have been named from the Indo-Pacific.

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[1] 1932, Rept. Michael Sars Exped. **4**, Pt. 1, p. 18, pl. 3.

[2] 1922, Fisher and Mar., Biol. Surv. S. Africa, Rept. **2**, p. 46, pl. 7, fig. 1.

[3] 1934, Proc. Acad. Nat. Sci. Philadelphia, **85**, pp. 237, 238.

[4] *Indicus* Brauer, 1908, Ergeb. Deutsch. Tiefsee Exped. **15**, p. 8, p. 14, fig. 1.

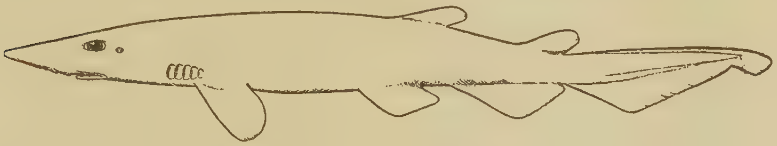

Fig. 1. *Apristurus profundorum*, type specimen, 510 mm. long, U. S. Nat. Mus., no. 35,646.

We therefore propose for it the new specific name *riveri*, after Dr. Luis Howell Rivero, in recognition of his contributions to knowledge of Cuban ichthyology.

Apristurus riveri new species

Plate VII

Study material: The type specimen, a female, 407 mm. long, trawled by the research ship 'Atlantis' of the Woods Hole Oceanographic Institution at Sta. 2993, off the north coast of Cuba, Lat. 23°, 24′ N., Long. 80°, 44′ W., March 15, 1938, in 580 fathoms, M.C.Z. no. 36,092.

Proportional dimensions, in percentages of total length of type specimen: Breadth of trunk at origin of pectoral, 10.1; height at origin of pectoral, 11.8; interorbital breadth of head, 6.6; snout to mouth, 9.3; to origin of first dorsal, 47.8; to origin of second dorsal, 57.7; to origin of upper caudal, 67.0; to origin of pectoral, 23.9; to origin of pelvics, 40.2; to origin of anal, 52.2; horizontal diameter of eye, 2.7; breadth of mouth, 6.1; height of mouth, 2.2; breadth between nostrils, 3.9; length of upper labial furrow, 2.1; of lower labial furrow, 2.5; length of first gill opening, 3.3; of second gill opening, 3.4; of third gill opening, 3.2; of fourth gill opening, 3.0; of fifth gill opening, 2.1; vertical height of first dorsal, 2.9; of second dorsal, 4.2; of anal, 3.7; length of base of first dorsal, 4.4; of second dorsal, 6.1; of anal, 13.7; interspace between first dorsal and second dorsal, 7.0; between second dorsal and caudal, 2.7; between anal and caudal, 0; length of upper margin of caudal, 33.0; of lower anterior margin of caudal, 10.1; pectoral outer margin, 10.1; inner margin, 4.9; distal margin, 7.7; distance from origin of pectoral to origin of pelvics, 18.5; from origin of pelvics to origin of anal, 12.5.

Description: Trunk highest and broadest opposite axil of pectoral, narrowing evenly rearward; caudal peduncle strongly compressed laterally, about one half as thick as deep; body sector (snout to cloaca) about as long as tail sector; dermal denticles moderately erect, with short pedicel, their blades with weak median crest and tridentate free margin, the median tooth much the longest; denticles slightly largest, relatively narrowest, and most closely spaced along upper sides of caudal. Head strongly flattened anteriorly and contracted laterally just anterior to outer end of nostrils, its dorsal outline noticeably concave, with a triangular belt of about one hundred and ten very prominent pores along the mid-zone anterior to eyes; snout thin, broadly rounded at tip, its length in front of mouth slightly less than half as great as distance from its tip to fifth gill opening, its lower surface with a belt of conspicuous pores in four rows along the mid-line. Eye oval, its horizontal diameter about twice its vertical, and nearly as long as distance between nostrils, its mid-point about opposite corner of mouth. Spiracle round, about one fifth as large as horizontal diameter of eye, situated close behind latter. Gill openings with their anterior margins so deeply concave in outline that the tips of the gill filaments on the first to fourth arches are exposed, but with the dorsal and ventral ends so close together that the successive margins form an apparent frame around the gill area as a whole; first to fourth gill openings slightly longer than horizontal diameter of the eye, or about four times as long as from posterior margin of eye to spiracle; fifth gill opening considerably shortest; fifth close in front of origin of pectoral. Nostrils moderately oblique and far apart, their inner corners about three times as far from tip of snout as from symphysis of upper jaw, their outer corners at outer edge of snout; the anterior margin obtusely triangular in outline with its inner edge expanded as a shor-finger-like process, directed inward, into the nasal cavity, and entirely concealed unless the nostril be spread open; posterior margin also expanded, in outline shown in pl. VII, fig. C. Mouth obtusely ovate, nearly three times as broad as high, its breadth about two thirds as great as length of snout in front of mouth, occupying only about one half the breadth of the head. Labial furrows very prominent, forming approximately a right angle at corner of mouth, when the latter is closed, the upper extending forward about one third the distance toward outer end of nostril, the lower (slightly the longer) reaching only a short distance past corner of the mouth (pl. VII, fig. A); teeth about $\frac{26-0-26}{25-0-25}$, uppers with three cusps, the median erect and much the longest, except toward corners of mouth where there may be as many as five cusps, with the median cusp curving outward; lowers similar to uppers in center of mouth, but usually with five cusps along sides of mouth, and with the median cusp only a little larger than the others; no teeth at symphysis in either jaw, but tooth next the symphysis in lower very small; mostly three rows functional in upper jaw, but two to four rows functional over short sectors; four rows functional in lower jaw, arranged in quincunx.

First dorsal very small, its base a little longer than horizontal diameter of eye, brush-shaped, with convex anterior margin and rounded tip, its origin over rear end of bases of pelvics. Second dorsal similar to first but nearly one and one half times as long at the base and slightly higher vertically, its origin about over mid-point of base of anal, interspace between second dorsal and caudal a little less than half as long as base of former. Caudal about one third of total length, with brush-shaped tip, well-marked subterminal notch, its lower anterior corner more obtuse than a right angle, its axis only very slightly raised, if at all. No measurable interspace between caudal and anal. Anal subquadrate, with rounded outer and angular rear corner, its base slightly more than twice as long as base of second dorsal. Pelvics a little less than half as long at base as anal, with rounded anterior and angular rear corner, their inner margins in female very short and entirely separate, one from the other, behind the cloaca. Interspace between pelvics and anal about two thirds as long as base of former. Pectorals a little more than one third as long as head, nearly as broad at base as at tip, with slightly convex anterior margin, nearly straight distal and inner margins, and rounded corners.

Colors (In alcohol): Uniform chocolate brown above and below; the tongue and lining of the mouth blackish.

Developmental stages: Not known.

Size: No information is available as to the length to which this species may grow. The specimen at hand does not contain eggs.

Range: Known only from specimen recorded above, taken off the north coast of Cuba. The depth of capture, combined with the uniformly dark coloration, suggests that this is a deep-water species.

Genus TRIAKIS Müller and Henle, 1838

Up to the present, this genus has been known only from the Indian Ocean (including the Red and Arabian Seas), from Malaysia and Polynesia, from the western North Pacific, and from the Pacific coasts of America, North and South.

In March, 1938, however, and again in May, 1939, the research ship 'Atlantis' of the Woods Hole Oceanographic Institution collected 38 specimens, clearly falling in this genus, but separated from all previous known members of it by the combined facts that the origin of its second dorsal fin is over the origin of the anal, instead of anterior to the latter, (in which its agrees with *venusta* Tanaka, 1912) and that the anterior marginal expansion of the nostril is far in advance of the front of the mouth. It is also characterized by very short labial furrows and strongly tridentate dermal denticles.

This find is of great interest from the zoö-geographical standpoint, for it adds one more to the list—already considerable—of animals that occur both on the Pacific coast of America on the one hand, and in the Carribean-West Indian region on the other, but are not known elsewhere in the Atlantic.

We name this new shark *barbouri*, after our friend and colleague, Dr. Thomas Barbour, in recognition of the constant assistance he has given us in our labors on sharks of the western North Atlantic.

Triakis barbouri new species

Plate VIII

Study material: 38 specimens, male and female, 225 to 338 mm. in total length, collected off the north coast of Cuba, March, 1938, and May, 1939, by the research ship 'Atlantis.' As the type, we have selected a male of 283 mm.[1]

Proportional dimensions of type, in percentages of total length: Breadth of trunk at origin of pectoral, 9.5; height at origin of pectoral, 8.8; length of snout in front of mouth, 5.6; in front of outer nostrils, 3.5; snout to origin of first dorsal, 31.4; to origin of second dorsal, 56.5; to origin of upper caudal, 73.2; to origin of pectoral, 20.4; to origin of pelvics, 39.2; to origin of anal, 57.8; horizontal diameter of eye, 3.9; breadth of mouth, 7.1; height of mouth, 3.5; distance between inner ends of nostrils, 2.9; length of upper labial furrow, 0.5; of lower labial furrow, 0.5; length of first gill opening, 1.8; of second gill opening, 1.8; of third gill opening, 1.8; of fourth gill opening, 1.8; of fifth gill opening, 1.4; vertical height of first dorsal, 4.9; of second dorsal, 4.2; of anal, 2.9; length of base of first dorsal, 6.9; of second dorsal, 8.8; of anal, 8.1; interspace between first dorsal and second dorsal, 16.9; between second dorsal and caudal, 7.6; between anal and caudal, 7.4; length of upper margin of caudal, 26.8; of lower anterior margin of caudal, 9.9; pectoral outer margin, 13.0; inner margin, 8.1; distal margin, 9.5; distance from origin of pectoral to origin of pelvics, 22.2; from origin of pelvics to origin of anal, 16.9.

Description: Trunk slender, its height abreast origin of first dorsal only about one seventh of its length to origin of caudal, its dorsal profile only slightly arched, its ventral profile nearly straight except in gravid females; tail sector (anus to tip of caudal) about one sixth longer than body sector; caudal peduncle laterally compressed, about twice as high as broad at origin of caudal, without lateral keels or precaudal pit above or below. Dermal denticles close-spaced and usually overlapping with short pedicels and horizontal blades, the latter regularly tridentate in outline, the median tooth narrow, and much the longest, with three ridges, the median ridge flat-topped distally but rounded proximally. Head (to fifth gill opening) about one fifth of total length, flattened above, its dorsal profile sloping steeply downward. Snout short, its length in front of mouth about one third of length of head to origin of pectoral, or a little less, its tip thin and broadly ovate. Eye oval, about three times as long as high, and noticeably large, its horizontal diameter about two thirds as long as snout in front of mouth; the larger specimens with a well-marked subocular fold, separated, however, from the margin of the lower eyelid at both ends when the latter is drawn down, but only faintly indicated when lower eyelid is drawn up over eyeball, or in small specimens even when the eye is wide open. Spiracle oval, its longest diameter only about one fifth to one sixth as long as horizontal diameter of eye, situated slightly below level of center of latter and behind it by a distance slightly less than half its own length. Gill openings very short, their outlines deeply concave anteriorly, the fourth-fifth over the origin of the pectoral, the first (longest) about half as long as the horizontal diameter of the eye, the second, third and fourth slightly shorter, the fifth considerably so and situated noticeably higher on the sides than the first four; interspaces between gill openings about one half to two thirds as wide as lengths of latter. Nostril moderately oblique, its inner corner a little less than one third as far from front of mouth as from tip of snout, its anterior margin expanded as a low, subquadrate lobe. Mouth ovate, occupying about three fourths of breadth of head, and a little more than half as high as broad, corner of mouth, with a very short labial furrow on each jaw. Teeth $\frac{62}{62}$, closely crowded, with those of successive rows overlapping; three (locally four) rows functional in front of upper jaw, but only two to three rows near corners, three to four rows functional in front of lower jaw, and five to six rows toward the angles where the serial arrangement is increasingly oblique; upper teeth with three cusps, the axial erect or slightly curved, and much the longest, but with blunt tip, and marked with irregular longitudinal striae basally; those toward corners of mouth somewhat smaller with relatively shorter median cusp and broader base than those in front of mouth; lowers similar to uppers toward center of mouth, except that the outer lateral cusp may be minute or lacking, but those along sides of jaw with (usually) two or three basal cusps on the inner side and none on the outer side, the cusp that is primarily median thus being at the outer edge of the tooth.

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[1] Mus. Comp. Zoöl., no. 36,099.

Origin of first dorsal a little behind inner corner of pectoral, its base about as long as from center of eye to first gill opening, its anterior margin very slightly convex, apex rounded, posterior margin slightly concave, its rear corner triangular, the free rear corner a little more than half as long as its base, rear end of base a little anterior to origin of pelvics. Second dorsal similar to first, and about as high, but about one and one half times as long at base, its origin about over that of anal, and slightly closer to origin of caudal than to rear tip of first dorsal. Caudal between one fourth and one third of total length, obliquely truncate at tip, with well-marked subterminal notch, and noticeably narrow, its lower contour obtusely triangular, with rounded lower anterior corner, the latter not exposed as a distinct lobe. Anal similar to second dorsal in shape and about as long at base, but only about two thirds as high; interspace between anal and caudal a little shorter than base of anal; that between anal and tips of pelvics a little more than half as long as base of anal. Pelvics subquadrate, with nearly straight anterior and distal margin, but slightly concave inner margin, and broadly rounded outer corners, their inner corners narrowly elongate in both sexes, with pointed tips. Pectoral about two thirds as broad as long, between two and three times as large in area as first dorsal, with slightly convex anterior and inner margins, very weakly concave distal margin, and narrowly rounded corners.

Color: Upper parts of trunk, caudal, dorsals and upper surfaces of pectorals pale gray, lower surface grayish white. In some specimens, at least, the anterior edges of the dorsals and of the caudal, midway of its length, are marked with faintly defined smoky blotches, reminiscent of the color pattern of the embryo, which (just before birth) shows more extensive blotches in these same general regions, besides a similar blotch on the upper side of the caudal peduncle, one on the back midway between the two dorsals, one on the side, just posterior to the pectoral; also a sooty area, irregular in outline, extending upward obliquely from the region of the gill openings to the dorsal surface of the nape.

Developmental stages: Two embryos, 90 to 100 mm. long, and nearly ready for birth, contained in a female 303 mm. long, resemble the parent, except that the caudal is relatively longer with slightly convex lower margin, the origin of the first dorsal relatively somewhat farther back, the dorsals more broadly rounded, the tips of the pelvics relatively much shorter, and the eyes relatively much larger (embryonic characters to be expected), and the color pattern not only more pronounced but more extensive, as noted above. There is no placental attachment between embryo and mother.

Size: Evidently this is one of the smallest of sharks. The facts that a female of only 303 mm. contained two large embryos, and that the claspers in a male of 338 mm. are very large, extending rearward as far as the origin of the anal suggests a maximum length perhaps not greater than about 350 to 400 mm. or about one foot, 2 to 4 inches.

Habits: The recorded depths of capture of this little shark range only between 235 and 335 fathoms (six stations), but since the trawls that yielded them were hauled up open, to the surface, they may have been swimming at some mid-depth, not on the bottom. Nothing more is known of their habits.

Range: So far known only off the north coast of Cuba, in the offing of the province of Santa Clara, where it must be tolerably plentiful, judging from the number of specimens taken.

Genus EULAMIA Gill, 1861

Eulamia springeri new species [1]

Study material: Type specimen, female, 805 mm. in total length, Cozumel, Yucatan, U. S. Nat. Mus. no. 37,141; also probably of this species is a somewhat shrivelled skin, with head, also female, about 1390 mm. in total length, Englewood, Florida, Mus. Comp. Zool., no. 35,900.

Proportional dimensions of type specimen, in percentages of total length: Breadth of trunk at origin of pectoral, 12.0; height at origin of pectoral, 11.4; length of snout in front of mouth, 6.6; in front of outer nostrils, 3.1; snout to origin of first dorsal, 30.7; to origin of second dorsal, 58.8; to origin of upper caudal, 70.2; to origin of pectoral, 20.5; to origin of pelvics, 47.9; to origin of anal, 58.8; horizontal diameter of eye, 2.1; breadth of mouth, 8.9; height of mouth, 5.7; distance between inner ends of nostrils, 6.5; length of upper labial furrow, 0.6; length of first gill opening, 2.3; of second gill opening, 2.6; of third gill opening, 2.7; of fourth gill opening, 2.6; of fifth gill opening, 2.2; vertical height of first dorsal, 10.7; of second dorsal, 3.3; of anal, 3.9; length of base of first dorsal, 9.9; of second dorsal, 4.5; of anal, 4.9; interspace between first dorsal and second dorsal, 20.7; between second dorsal and caudal, 7.7; between anal and caudal, 6.1; length of upper margin of caudal, 29.8; of lower anterior margin of caudal, 14.2; pectoral outer margin, 19.9; inner margin, 5.2; distal margin, 15.6; distance from origin of pectoral to origin of pelvics, 27.2; from origin of pelvics to origin of anal, 11.0.

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[1] So named in recognition of the fact that it was Mr. Stewart Springer who first recognized that the type specimen represented a species not previously described.

Description of type: General form moderately stout, the trunk about one fifth as high at origin of first dorsal (where highest) as long to origin of caudal; body sector (to cloaca) a little longer than tail sector; mid-line of back with a low but unmistakable dermal ridge between dorsals. In the preserved state, there is also a similar ridge between the second dorsal and caudal. Since, however, this lies along the bottom of a groove of muscular contraction, we question whether it is a normal feature. Upper precaudal pit strongly marked, sub-angular in outline; lower pit less distanct than upper, but similar to it in form. Dermal denticles closely and regularly overlapping, broader than long, with five (sometimes seven) short, marginal teeth, and an equal number of low ridges. In the larger specimen, probably of this species, the denticles usually have seven ridges, and teeth. Head (to origin of pectoral) a little less than one third of length to origin of caudal, moderately flattened above. Snout broadly rounded, its length, anterior to a line connecting outer ends of nostrils, a little less than half as great as length in front of mouth, and length in front of mouth nearly three fourths (74%) as great as breadth of mouth, or about one third of length of head to origins of pectorals. Eye approximately circular, its diameter a little more than one third as long as distance between nostrils and about as long as first gill opening. Third gill opening (a little the longest) a little more than two fifths (42%) as long as distance between nostrils; fifth about four fifths as long as third, and more oblique than the others; third gill opening above origin of pectoral. Nostril strongly oblique, its inner corner nearer to the mouth than to the tip of the snout by a distance a little longer than its own length, or than the diameter of the eye, its anterior margin expanded toward the inner end as a distinct, though low, subtriangular lobe. Mouth broad-ovate, a little less than two thirds (about 62%-63%) as high as wide. Teeth $\frac{12-1-13}{12-1-13}$; upper teeth triangular, first and second erect and nearly symmetrical, with concave margins and expanded bases, but subsequent teeth unvaryingly oblique, toward corners of mouth, their inner margins nearly straight, but their outer margins more and more deeply concave, in subangular contour, the outermost strongly so; margins regularly serrate, tip to base, and much the most strongly so outwardly, on basal sector. Lower teeth nearly erect, except for the outermost three or four, which are moderately oblique, their cusps much more slender than those of uppers, on broadly expanded bases, their margins much more finely serrate than those of uppers. One small symmetrical tooth at symphysis, and outermost three to five successively smaller, in each jaw. Origin of first dorsal, a little anterior to inner corner of pectoral, its base nearly as long as from posterior edge of eye to first gill opening, its vertical height about equal to its base, its anterior margin only weakly convex toward the apex, posterior margin only weakly concave (less so than in *obscurus*), apex narrowly rounded; free rear corner only about one third to one fourth as long as the base, (thus relatively shorter than in *obscurus*); mid-point of base about 1.7, as far from origin of pelvics as from axil of pectoral. Second dorsal between one half and one third as long at base as first, relatively lower, its vertical height about two thirds as great as its length at base, its free rear corner a little shorter than its base, its posterior margin weakly concave; its extreme length, origin to rear tip, about 2.5 as great as the vertical height, thus considerably shorter relative to its height than in *obscurus*, its origin a very little anterior to that of anal. Caudal between one third and one fourth (30%) of total length; its terminal sector about one fourth the total length of the fin, slender, with narrowly rounded tip and weakly concave lower posterior outline; lower lobe, (expanded lower anterior corner) only a little less than half (about 47%) as long as upper, each measured from the respective precaudal pit, thus somewhat longer, relatively, than in *obscurus*, with weakly convex anterior margin, nearly straight posterior margin, and narrowly rounded tip; reëntrant corner, included by the two lobes, well rounded. Distance from origin of caudal to tip of anal about two thirds as long as base of latter. Anal a little longer at base than second dorsal, and a very little higher, vertically, its posterior margin much more deeply concave; free rear corner about two thirds as long as the base. Distance from origin of anal to tips of pelvics only about three fourths as long as base of anal. Pelvics about as long at base as base of anal, or a little longer, their outer corners approximately a right angle (less obtuse than in *obscurus*). Pectoral about four fifths as long as head, a little less than half as broad as long, with narrowly rounded tip and inner corner, weakly and evenly convex anterior margin, and distal margin deeply concave proximally.

Color: After preservation, the type specimen is olive gray above, and of a paler shade of yellowish olive below, without conspicuous fin markings, either dark or light.

Size: The fact that the type specimen still shows the umbilical scar, although 805 mm. long, suggests that this is one of the larger members of its genus.

Distinctive characters: *E. springeri* most nearly resembles *E. obscurus*, with which it agrees in general, so far as relative sizes and positions of fins are concerned, and in the presence of a mid-dorsal ridge. But it differs in a number of features (in combination) from specimens of *obscurus* of approximately the same size, with which we have compared it: (a) its eye is considerably larger, relative to the lengths of the gill openings; (b) the anterior margin of its nostril is expanded as a low, triangular lobe (not lobed in *obscurus*); (c) its first dorsal is relatively larger and more erect, but with its free rear corner relatively shorter and the posterior margin less deeply concave; (d) its second dorsal is larger in area, but shorter—origin to rear tip—relative to its vertical height; (e) the distance from the tips of its pelvics to the origin of its anal is considerably shorter (about 0.7 the anal base in *springeri*, but 1.3 the anal base in *obscurus*); (f) the outer corners of its pelvics are only about a right angle (about 115° in *obscurus*); (g) its denticles have a larger number of marginal teeth and of ridges in specimens of equal size; and (h) its upper teeth are more strongly oblique, more deeply incised, outwardly, and more coarsely serrate basally than those of *obscurus*.

Among Eulamias of the west coast of America, *springeri* resembles most nearly *platyrhynchus* Gilbert, 1891, in its teeth, and in its fins. But the length of its snout (in front of mouth) is considerably less than the breadth of the mouth (a little longer than the breadth of the mouth in a specimen of *platyrhynchus*, with which we have compared it); and its fins show no trace of the white edgings that are so conspicuous in *platyrhynchus*, differences that seem sufficient to demand recognition in nomenclature, and especially so in view of the geographic discontinuity between the areas of occurrence of the two sharks in question

Springeri is sharply separated from *galapagoensis* Snodgrass and Heller, 1905, the teeth and snout of which are similar, by the shapes of the first dorsal and pectoral fins, by its much larger eye (relative to the lengths of the gill openings), and by the fact that its second dorsal is only very little smaller than its anal, in area.

Genus SOMNIOSUS Lesueur, 1818

It seems sufficiently established that the 'Greenland' sharks of the subarctic province of the two sides of the North Atlantic belong to a single species, *S. microcephalus* Bloch and Schneider, 1801. But it is still an open question, just what the relationship is between it, and the very much smaller form that has been reported repeatedly from the Mediterranean and from the coast of Portugal, as *rostratus* Risso, 1826. If, however, the more recent of the illustrations of the latter can be accepted as reliable, it differs from *microcephalus* in a relatively much shorter interspace between the tip of the second dorsal and the caudal, in its relatively larger fins, in its smaller dermal denticles, in the presence of strongly developed luminous organs, and in various skeletal characters, as well as in attaining maturity at a much smaller size, and—most important of all—in the fact that it is ovoviviparous.

The North Pacific representative of the genus has usually been thought identical with the North Atlantic *microcephalus*. However, the first dorsal stands considerably farther rearward in a Japanese specimen that we have examined,[1] than is ordinarily the case in North Atlantic specimens. The lower anterior and upper posterior margins of the caudal are much more strongly convex, the distance from the tip of the second dorsal to the origin of the caudal much shorter relatively, upper teeth considerably broader, and the basal outline of the lower teeth more deeply incised in the Pacific than those in the North Atlantic.

These differences seem sufficient for recognition in nomenclature, and to do so, a new specific designation for the Pacific form appears necessary, because every previous mention of it, in scientific literature has been under one or another of the names that actually belong to the North Atlantic species. To remedy this deficiency, we propose for it, the new specific name *pacificus*.

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[1] This is the specimen illustrated by Garman, 1913, Mem. Mus. Comp. Zoöl. **36**, pl. 14, figs. 1–3, as "*brevipinna*."

The differences between the Atlantic and Pacific species may be summarized as follows:

A. Origin of first dorsal, about as far from axil of pectoral as from origin of pelvics; distance from tip of second dorsal to origin of caudal only about half as long as base of second dorsal. Caudal with posterior margin of terminal sector moderately convex, and lower anterior margin strongly so; cusps of upper teeth nearly as broad, basally, as they are long; lower teeth very deeply incised, basally.

pacificus, n. sp.

B. Origin of first dorsal not more than half as far from axil of pectoral as from origin of pelvics; distance from tip of second dorsal to origin of caudal nearly or quite as long as base of second dorsal. Caudal with posterior margin of terminal sector nearly straight, and lower anterior margin only moderately convex; cusps of upper teeth much narrower than long; lower teeth not deeply incised basally.

microcephalus Bloch and Schneider, 1801.

EXPLANATION OF PLATES

Plate VII.	*Apristurus riveri*, type specimen, 407 mm. long; (A) lower side of head; (B) gill openings, enlarged; (C) right-hand nostril, enlarged; (D) dermal denticles; (E) teeth, upper and lower, three rows from center and one row from outer part of jaws, × about 10.
Plate VIII.	*Triakis barbouri*, type specimen, 285 mm. long; (A) lower side of head; (B) pelvic fins and claspers; (C) upper teeth from side of jaw, × about 15; (D) lower teeth from center of jaw, from side of jaw, and from outer part of jaw, left to right, × about 10; (E) dermal denticles.
Plate IX.	*Eulamia springeri*, type specimen, 805 mm. long; (A) under side of head; (B) nostril × about 1.5; (C) cross section of back between first and second dorsal fins, to show dermal ridges.
Plate X.	*Eulamia springeri*, (A) upper and lower teeth, × about 2; (B) fourth and eighth upper teeth, and third and ninth lower teeth, counted from symphysis, more enlarged; (C) dermal denticles × about 30.

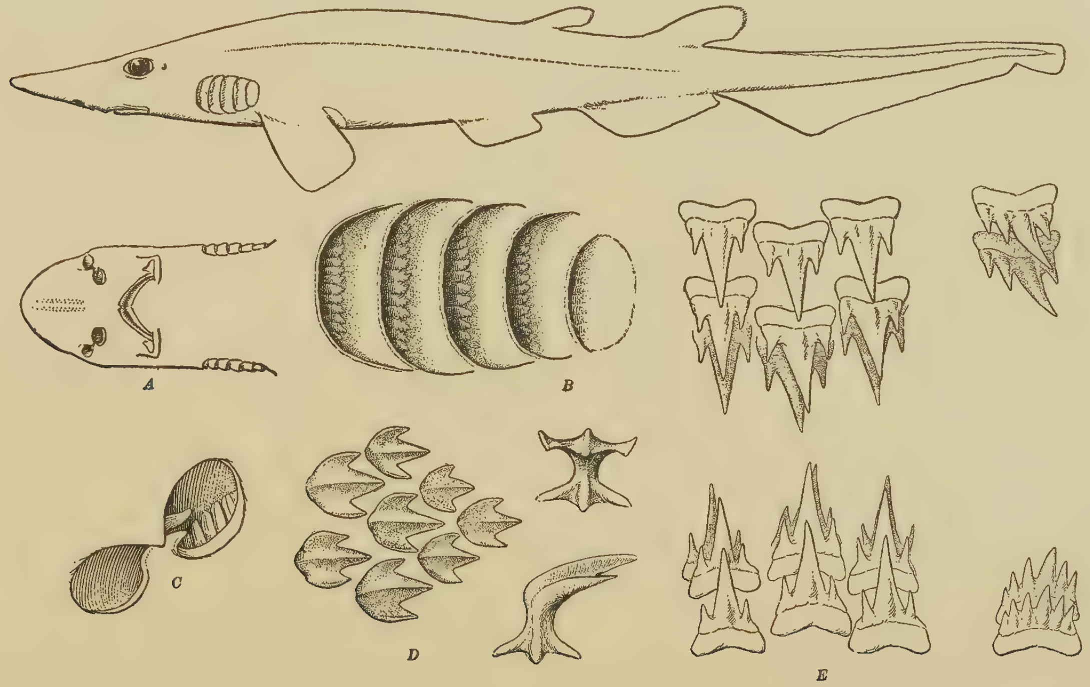
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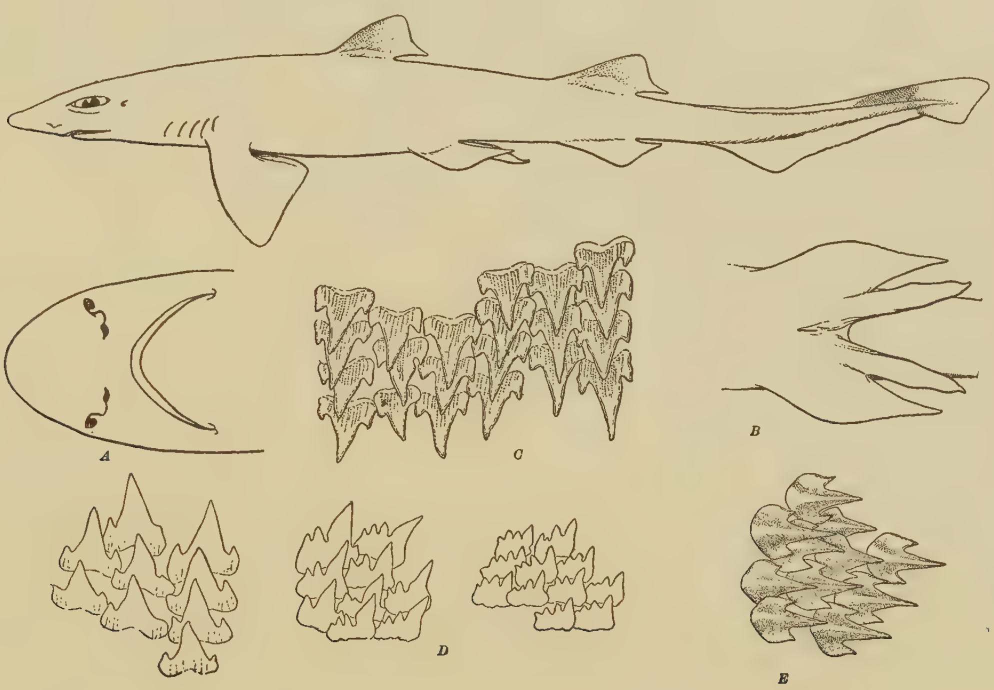
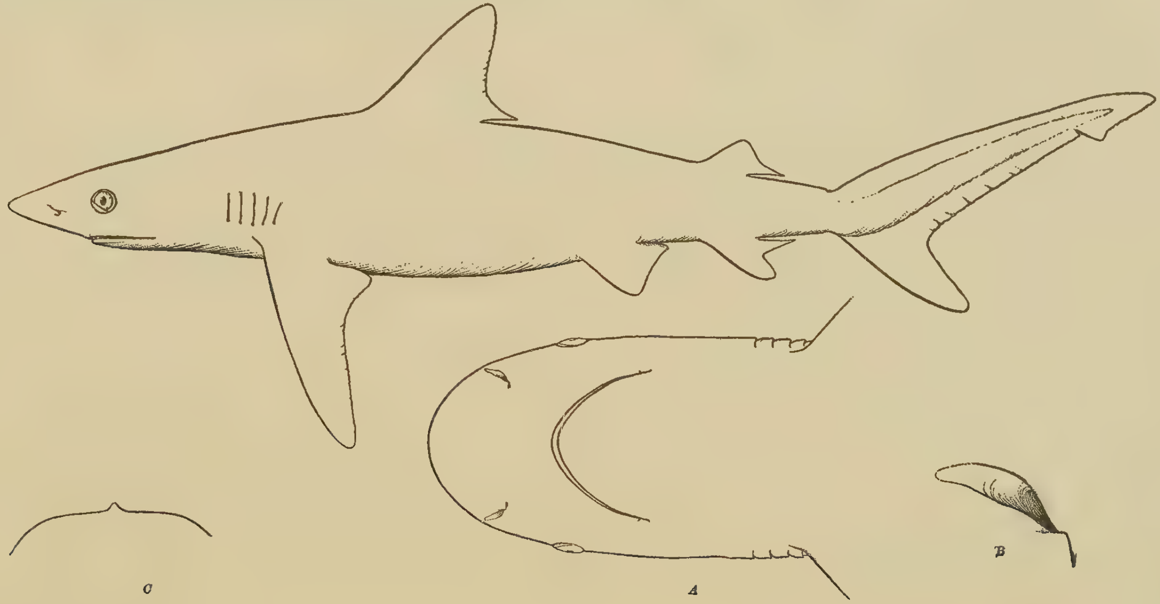
Plate VIII

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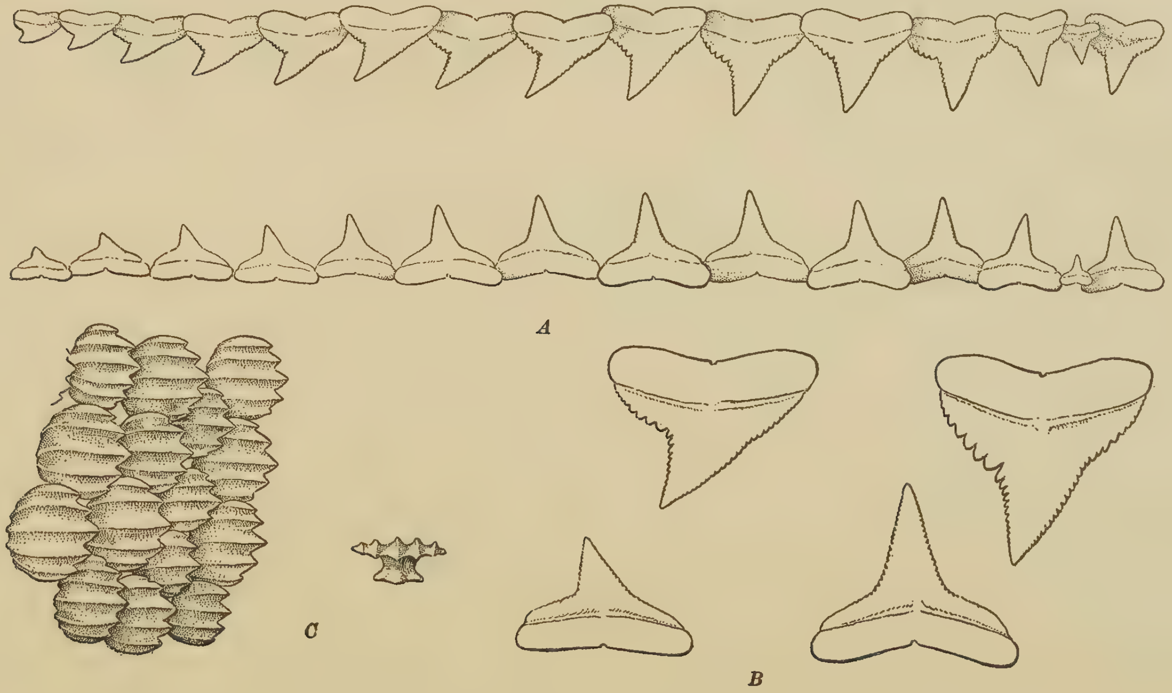
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Contribution No. 334

A NEW TROPICAL BUCCINUM FROM CUBA (*)

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From among the *Atlantis* and the *Blake* dredgings, there is a rather distinctive *Buccinum* occurring in fairly deep water in the West Indies. This genus is uncommon, as few, if any, species have been obtained from southern waters, even deep waters of the tropical Western Atlantic.

Buccinum canetae new species

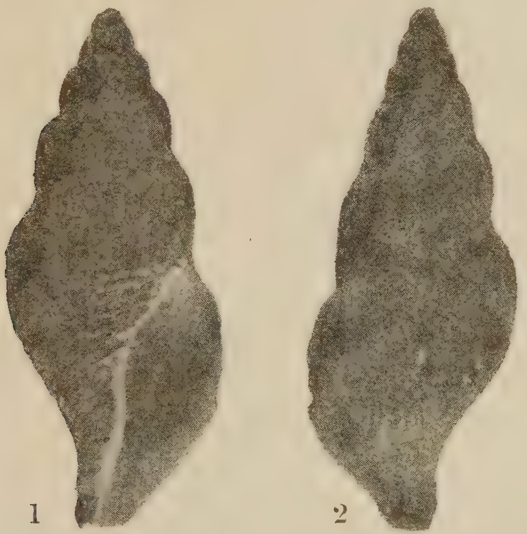

Fig. 1. — Holotype, off Habana, Cuba; fig. 2. — Paratype, off Barbados.

Description. — Shell heavy, 68 mm. in length (about 2¾ inches), solid, rather extended, imperforate and strongly sculptured. Whorls 7 to 7½, rather globose and regularly increasing in size. Color a dull medium brown. Columella and interior of aperture porcellaneous white. Aperture subovate and extending below with a short but wide canal. Outer lip thin; inner lip glazed smooth and white. Suture well defined but not deeply indented. Axial sculpture of numerous and strong ridges which become rather less pronounced on the body

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(*) Contribution No. 334, Woods Hole Oceanographic Institution.

whorl. Spiral sculpture of many flattened and rather narrow chords. Periostracum rather strong and persistant in between the spiral chords with five axial growth lines showing. Operculum unguiculate, with an apical nucleus and possessing numerous and rather coarse concentric growth lines.

Length	*Width*	
68	29.5 mm.	Holotype
67	27.0 mm.	Paratype

Holotype, Museum of Comparative Zoology, No. 145740, *Atlantis,* Station 3003, off Habana, Cuba (N. Lat. 23°12'30"; W. Long. 82°12') in 240 to 300 fathoms. Paratype, *Blake,* Station 281, off Barbados, Lesser Antilles, in 288 fathoms.

Remarks. This is a narrow and compact shell possessing a rather heavy periostracum. Only two examples are known, the holotype from off Habana was collected alive, the Barbados specimen was collected dead but in fairly good condition.

This species was named for Sra. Isabel Pérez Farfante (Mrs. Gerardo Canet).

Contribution No. 335

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Evaluation of Antifouling Paints by Leaching Rate Determinations

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A method is described for measuring the rate at which copper toxics dissolve from antifouling paints, and conditions are given under which a significant value for the copper leaching rate will be obtained. It has been found that the leaching rates of antifouling paints change upon immersion in the sea. It is therefore necessary to determine leaching rates after various times of immersion to interpret adequately the antifouling properties of a paint. Evidence is presented which shows that the copper antifouling paints must leach at the rate of about 10 micrograms of copper per sq. cm. per day in order to prevent the attachment and growth of fouling organisms. All paints which have leaching rates consistently below this value become fouled. The leaching rate test permits quantitative measurement of the toxicity of an antifouling paint surface and has been useful in the study of new and improved formulations.

MANY theories have been proposed to explain the action of antifoulingpaints (*16*), but the development of such paints has been handicapped for lack of a clear understanding of the properties essential to satisfactory antifouling performance. Many investigators (*1*, *9*, *17*, *20*), however, have noted that the most effective paints contain a toxic material, usually a compound of copper or mercury, and specifications (*2*, *12*) for the toxic ingredients have been issued. The concept that the toxic material must be able to dissolve in seawater to exert its effect has been held by some workers (*9*, *15*, *20*), but no critical test of this concept has been available. It has been shown that the effectiveness of copper and copper-base alloys is related to the toxic effect of their products of corrosion (*5*, *7*, *10*, *14*). LaQue (*10*) estimated that the average solution of 7 to 10 mg. of copper per sq. dm. per day was sufficient to prevent fouling growth.

This paper describes a method for testing the rate at which copper leaches from antifouling paints. The practical interest in the test depends on the assumption that the prevention of fouling is related to the concentration of toxic dissolved in the water at the surface of the paint, and that the rate of loss of toxic is a measure of the steady-state concentration in a narrow zone at the paint surface. Experience gained in three years of study at the Woods Hole Oceanographic Institution and the Mare Island Navy Yard indicates that the prevention of fouling by the paint is directly related to the leaching rate as determined by the method described in this paper.

Previous attempts have been made to measure the loss of toxics from antifouling paints. Orton (*13*) and Edmondson and Ingram (*8*) measured the loss of copper and other toxics from painted surfaces by determining their content in the paint before and after soaking in the sea. Bray (*3*), Edmondson and Ingram (*8*), Whedon and collaborators (*18*), and Miller and Cupp (*11*) have determined the toxicity of solutions in which painted panels had been soaked for a definite period. None of these tests have proved practical as a guide for the formulation of paints.

When a glass or metal panel coated with a copper paint is soaked in a beaker of sea water, copper is liberated and accumulates in the water. The initial rate of solution is defined as the leaching rate of the paint. The following conditions have been found convenient:

PANELS. Sandblasted glass panels, 3 × 4 inches, are painted on both sides. Similar results are obtained if primed steel panels are used, but the presence of iron in solution interferes with the colorimetric determination of copper. After painting, the panels are allowed to dry for 1–4 days. Prolonged drying times change the results obtained with some paints.

LEACHING SOLUTION. Clean aerated sea water is used as the leaching solution. The pH of the solution should be between 8.0 and 8.2, and the chlorinity of the sea water should be 17 parts per thousand. The ratio of the area of paint exposed (in square centimeters) to the volume of leaching solution (in cubic centimeters) is 1: 5. Thus, one 3 × 4 inch (150 sq. cm.) panel is leached in 750 cc. of sea water, two panels in 1500 cc., etc. If panels of a different size are to be used, the volume of solution should be selected to maintain this ratio.

AGITATION. The solution is agitated by a rapid stream of air bubbles delivered at the base of the beaker by a 7–8 mm. i.d. glass tube.

TIME OF SAMPLING. The sample should be taken before the concentration of copper in solution exceeds 0.5 microgram per cc. Above this concentration the rate of solution from the paint decreases and insoluble compounds of copper are precipitated.

For routine determinations a specific sampling time may be selected. A leaching rate measured after 2 hours will give accurate results if the value is 30 micrograms per sq. cm. per day or less, a 4-hour sample if the value is 15 or less, etc.

Analytical Method. Copper analyses were made by the diethyl dithiocarbamate colorimetric method described by Callan and Henderson (*4*) and Coulson (*6*). A 50-cc. sample of the leaching bath is treated with citric acid, ammonium hydroxide, and sodium diethyl dithiocarbamate, as described by Coulson. Amyl acetate is used to extract the yellow copper salt of diethyl dithiocarbamic acid from the sea water. The quantity of copper present is determined with a properly calibrated Klett-Summerson photoelectric colorimeter, using a green filter (No. 54, approximate spectral range 500–590 millimicrons) for solutions containing between 0.3 and 2.0 micrograms per cc. and a blue filter (No. 42, approximate spectral range 400–465 millimicrons) for solutions containing less than 0.4 microgram per cc.

Calculations. The leaching rate is defined as the number of micrograms of copper liberated from a square centimeter of paint surface per day. It is calculated according to the equation:

$$\begin{aligned}\text{leaching rate} &= \mu\text{g./cc.}\left[\frac{\text{volume (cc.)} \times 24}{\text{area of paint (sq. cm.)} \times \text{time (hr.)}}\right]\\ &= \mu\text{g./sq. cm./day}\end{aligned}$$

(This unit is numerically equivalent to mg. per 1000 sq. cm. per day, which is currently used by the Navy paint laboratories. The results obtained in these units must be divided by 10 to convert to mg. per sq. dm. per day, the unit frequently used in corrosion studies.)

SOLUTION OF COPPER FROM TYPICAL PAINTS

Typical data for the total amount of copper dissolved by 750 cc. of sea water from 3 × 4 inch panels painted with a metallic copper, a red copper, and a green copper paint of commercial origin are given in Figure 1. A precipitate appeared in the beakers containing the metallic copper and cuprous oxide paints after the first few hours. When a sample was taken for analysis, the solution was stirred vigorously to ensure that a fair sample of the precipitate was included.

The metallic copper paint liberated copper initially at a rapid rate which gradually decreased with time. The rate of dissolution of copper from the cuprous oxide paint decreased appreciably after a concentration of 1 microgram per cc. was reached. No further copper leached from the green paint after a concentration of 0.5 microgram per cc. was reached. These relations appear to be characteristic for the types of paint studied.

Under service conditions a paint is being bathed continuously with fresh sea water. This condition is represented in the test only by the initial rate of leaching. The accumulation of copper which occurs as the test proceeds, and which ultimately slows down the rate of dissolution of copper, has no counterpart under service conditions. Consequently, only the initial slope of each curve in Figure 1 gives the "leaching rate" of the paint.

FACTORS INFLUENCING LEACHING RATE

The concentration of copper dissolved from an antifouling paint in any period of time depends upon the rate of agitation, the temperature, the volume of the solution, and the area of the panel used. The pH and chloride ion concentration of the leaching bath also have a pronounced effect. The latter are sufficiently constant if clean aerated sea water is used for the determination. Some of the observations are summarized here to aid in defining the conditions under which accurate results may be obtained.

It is necessary to agitate the leaching bath adequately to ensure that the leaching rate measured is characteristic of the paint and not limited by the diffusion of dissolved copper away from the surface. The results of an experiment to determine the rate of stirring necessary to give maximum values for the leaching rate are given in Table I. Results obtained when a painted microscope slide, sealed to the bottom of a cylindrical flask, was rotated at 30 r.p.m. about its own axis are included as an example of mechanical stirring. The results show that the agitation is most critical at short times when rapid dissolution of

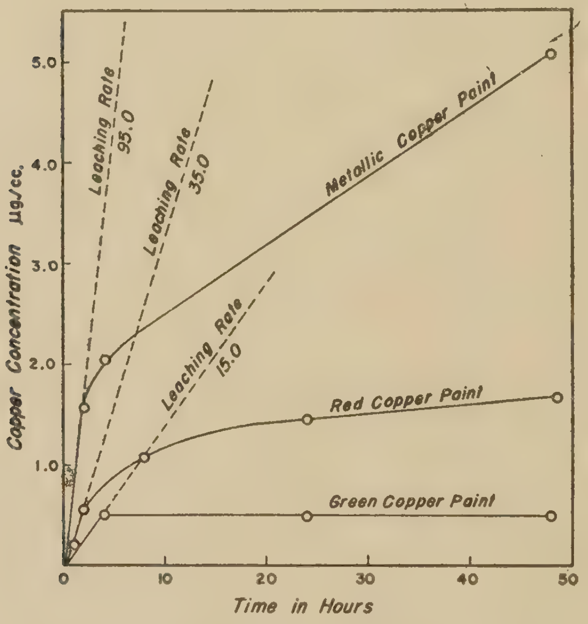

Figure 1. Dissolution of Copper from Copper Paints

Panels were freshly painted, and one panel of 150 sq. cm. area was leached in 750 cc. of sea water. Leaching rates in micrograms per sq. cm. per day.

TABLE I. EFFECT OF STIRRING RATE ON LEACHING OF COPPER FROM A COLD PLASTIC CUPROUS OXIDE PAINT

(Conditions: stirring, one 3 × 4 inch painted panel in 750 cc. of sea water; rotation, one 1 × 3 inch painted panel in 190 cc. of sea water)

Stirring	Copper Concn., μg./cc., after:			
	1 hr.	2 hr.	$4^1/_2$ hr.	8 hr.
Violent bubbling	0.29	0.56	1.00	1.07
10 bubbles/sec.	0.21	0.43	0.88	1.02
2 bubbles/sec.	0.16	0.33	0.76	0.96
No stirring	0.11	0.20	0.49	0.58
Rotation 30 r.p.m.	. .	0.53	. .	1.12

Table II. Leaching of a Cold Plastic Cuprous Oxide Paint in 1500 Cc. of Sea Water (Vigorous Agitation)

No. of Panels	Area *A*, Sq. Cm.	Time *t*, Hours	Area × Time, *At*	Copper Concn., μg./cc.
1	155	$^1/_2$	78	0.16
1	155	1	155	0.26
2	310	$^1/_2$	155	0.29
1	155	2	310	0.44
2	310	1	310	0.54
4	620	$^1/_2$	310	0.53
1	155	4	620	0.81
2	310	2	620	0.76
4	620	1	620	0.87
1	155	8	1240	1.15
2	310	4	1240	1.17
4	620	2	1240	1.17
2	310	8	2480	1.34
4	620	4	2480	1.31
4	620	8	4960	1.46

copper is occurring—i.e., during the period on which the leaching rate calculations are based. As the rate of dissolution diminishes, the rate of stirring becomes less important.

It should be pointed out that the higher the leaching rate, the more violent is the stirring required to keep pace with dissolution. Even violent bubbling may give inadequate agitation with paints having a high leaching rate. For such paints a mechanical means of stirring may be necessary.

The concentration of copper dissolved in the leaching bath in a given time will depend on the area of the panel and on the volume of sea water used. The curves in Figure 1 are, therefore, characteristic of the paint area and volume of solution as well as of the paint being studied. Data in Table II show that, in a given volume of solution, an approximately constant amount of copper is dissolved from the paint for equal values of the product, area × time. Table III shows that the effect of changing the volume of the leaching bath is the opposite of changing the paint area, and that approximately equal concentrations are obtained when the quantity (area × time)/volume is maintained constant. In the large-volume leaching baths vigorous bubbling was used to ensure adequate agitation.

The copper concentrations from Tables II and III are plotted in Figure 2 against At/V. The initial slope of the line in this figure is the leaching rate of the paint. It is clear from this

Table III. Leaching of a Cold Plastic Cuprous Oxide Paint at a Constant Value of 0.21 for (Area × Time)/Volume (Vigorous Agitation)

No. of Panels	Size of Panels, Inches	Area, Sq. Cm.	Time, Hours	Volume, Cc.	Copper, μg./cc.
1	8 × 10	1030	2	10,000	0.55
2	8 × 10	2060	1	10,000	0.43
1	3 × 4	155	2	1,500	0.41
2	3 × 4	310	1	1,500	0.43
4	3 × 4	620	$^1/_2$	1,500	0.41
1	1 × 3	39	1	190	0.41
2	1 × 3	78	$^1/_2$	190	0.43

figure that accurate results will be obtained only if the time for sampling the leaching bath is selected so that the concentration of copper is less than 0.5 microgram per cc. If the concentration is allowed to exceed this value, the leaching rates calculated will be low.

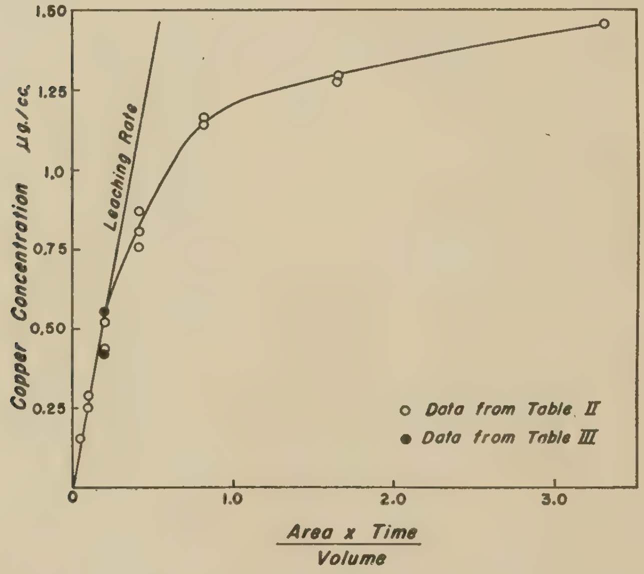

Figure 2. **Relation of Copper Concentration in Leaching Bath to Area of Panel × Time of Leaching ÷ Volume of Leaching Bath**

The temperature of the water in the leaching bath has a considerable influence on the initial leaching rate of a cuprous oxide paint. The data in Table IV show that during the period of rapid dissolution a fourfold increase in concentration is observed as the temperature is increased from 1° to 40° C. For practical purposes it has been found adequate to determine leaching rates at room temperature (20° C.). In the neighborhood of this temperature there is a variation in the leaching rate of about 3% per ° C.

LEACHING RATE FOR CHARACTERIZING ANTIFOULING PAINTS

It has been found that all paints change in leaching characteristics on immersion in the sea. The changes in leaching rates of several typical paints are shown in Figure 3. In this experiment a painted, 3 × 4 inch, ground-glass panel was leached in 750 cc. of sea water with vigorous bubbling, and a sample withdrawn for analysis after 4 hours ($At/V = 0.81$ hr. cm.$^{-1}$). The leaching rates with a value of 15 micrograms per sq. cm. per day or less are accurate under these conditions. All of the higher rates resulted from a copper concentration of more than 0.5 microgram per cc. and are consequently lower than would be obtained if the leaching bath had been sampled at shorter times. After the leaching test, the panels were placed in wooden racks and immersed in the sea. At monthly intervals they were removed from the racks, and the leaching rate determination was repeated under the same conditions. Each curve in Figure 1 represents the history of an individual paint panel. The dashed line is drawn at the minimum leaching rate essential for the prevention of fouling which, as will be shown in the next section, is 10 micrograms of copper per sq. cm. per day.

TABLE IV. EFFECT OF THE TEMPERATURE OF LEACHING BATH ON SOLUTION OF COPPER FROM A COLD PLASTIC CUPROUS OXIDE PAINT

(Conditions: one 3 × 4 inch panel in 750 cc. of sea water, vigorous bubbling)

Temp., ° C.	Time, Hr.	Copper Concn., μg./cc.
1	1	0.26
18	1	0.48
22	1	0.57
26	1	0.65
40	1	1.04

Four different responses to sea immersion are given in Figure 3. Curve *A* shows a moderately high initial leaching rate which, after two-month immersion, dropped to an inadequate value. At this time the paint became fouled. Curve *B* shows a leaching rate which never exceeded the essential value. Paints such as this become fouled immediately upon exposure to intense fouling conditions. Curve *C* shows a low initial leaching rate which had increased to an adequate value by the end of one month. This was maintained for six or seven months. Such paints may foul when initially immersed in the sea. If they survive the initial period, however, they remain free of fouling until the leaching rate again falls to low values. Curve *D* shows a high initial leaching rate which decreased, although adequate values were maintained for the duration of the exposure. This is the most satisfactory type of paint since it is always safe from fouling attachment, and it is capable of maintaining an adequate leaching rate as long as the paint lasts. The life of the paint is determined by the thickness of the film. This particular paint, exposed at Point Reyes, Calif., for 24 months, is still free from fouling. A panel exposed at Miami Beach, Fla., was free from fouling for twenty months, and is still only slightly fouled after twenty-seven months of exposure.

It is obvious from these data that the leaching rate determination is characteristic of the paint only at the time the measurement is made. It is not possible to predict the future behavior of a paint from any single leaching rate determination.

Young, Schneider, and Seagren (*21*) presented hypothetical curves to describe the changes which might be expected in the concentration of toxic at the interface after various times of immersion. Some of their curves are very similar to the data in Figure 3.

MINIMUM ADEQUATE LEACHING RATE

During the course of three years' study, leaching and fouling tests have been performed on several hundred formulations. The fouling characteristics of practically all these paints are accurately portrayed by their leaching rates. Some examples of the correlations obtained are given in this section.

A series of paints, all of which had the same matrix, were made up to contain graded amounts of cuprous oxide. The pigment volume content was maintained constant in all paints by substitution of magnesium silicate for cuprous oxide. Leaching rates during the first eight months of sea immersion were measured on panels at Woods Hole (Table V). Steel panels painted with the same paints were exposed at Tahiti Beach for tests of antifouling performance.

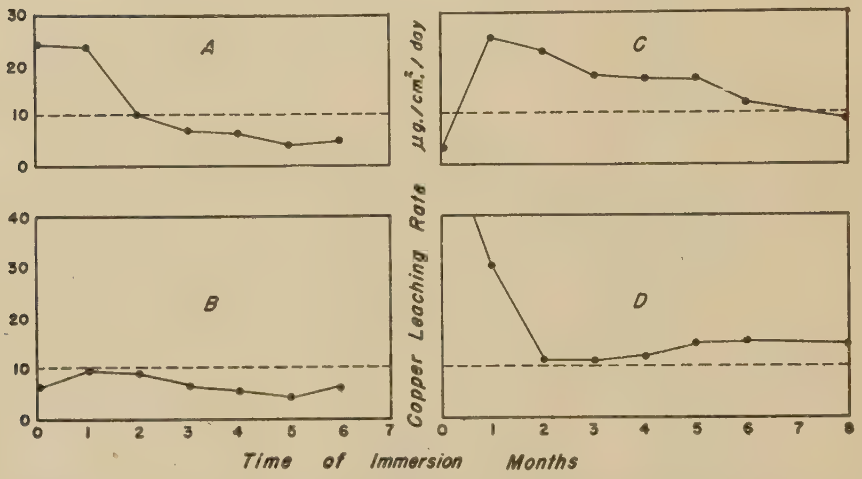

Figure 3. Changes of Leaching Rate of Four Typical Paints after Various Periods of Immersion in the Sea

TABLE V. LEACHING RATES OF COLD PLASTIC PAINTS CONTAINING GRADED AMOUNTS OF CUPROUS OXIDE

Paint No.	% Cu_2O in Dry Paint	Leaching Rate, μg. Cu/Sq. Cm./Day, after: 0	1 mo.	2 mo.	3 mo.	4 mo.	5 mo.	6 mo.	8 mo.
1	0.4	1.1	1.0[a]	0.6[a]	1.3[a]	0.3[a]	0.6[a]	0.1[a]	0.6[a]
2	1.23	2.9	1.2[a]	0.9[a]	1.7[a]	0.6[a]	0.6[a]	0.3[a]	0.9[a]
3	2.23	5.0	1.3[a]	0.9[a]	3.1[a]	0.9[a]	0.9[a]	1.2[a]	...
4	4.64	17.8	3.9[a]	1.6[a]	2.4[a]	1.9[a]	2.8[a]	2.5[a]	1.2[a]
5	9.3	25.0	7.5	4.7[a]	4.4[a]	1.9[a]	3.7[a]	7.1[a]	3.3[a]
6	13.8	27.4	14.1	11.3	10.0	10.5	Lost	...	...
7	19.2	40.6	19.3	11.3	8.8	8.1	10.1	8.0	8.1
8	24.8	51.5	27.7	12.5	9.5	12.2	12.3	9.8	9.0
9	30.0	55.1	28.5	13.4	9.7	10.3	13.8	14.4	13.8
10	36.0	57.4	30.2	11.6	10.9	12.0	14.4	14.7	14.1
11	50.7	47.2	44.3	21.0	14.2	15.6	20.2	18.7	17.7

[a] Formulations which fouled when exposed at Tahiti Beach for the indicated time.

By the fourth month of exposure at Tahiti the surfaces of the first five paints were completely covered with fouling (Figure 4). The total amount of fouling increased as the cuprous oxide content decreased. No fouling attachment of any kind was found on paints 6 to 11, inclusive, at any time during the course of the

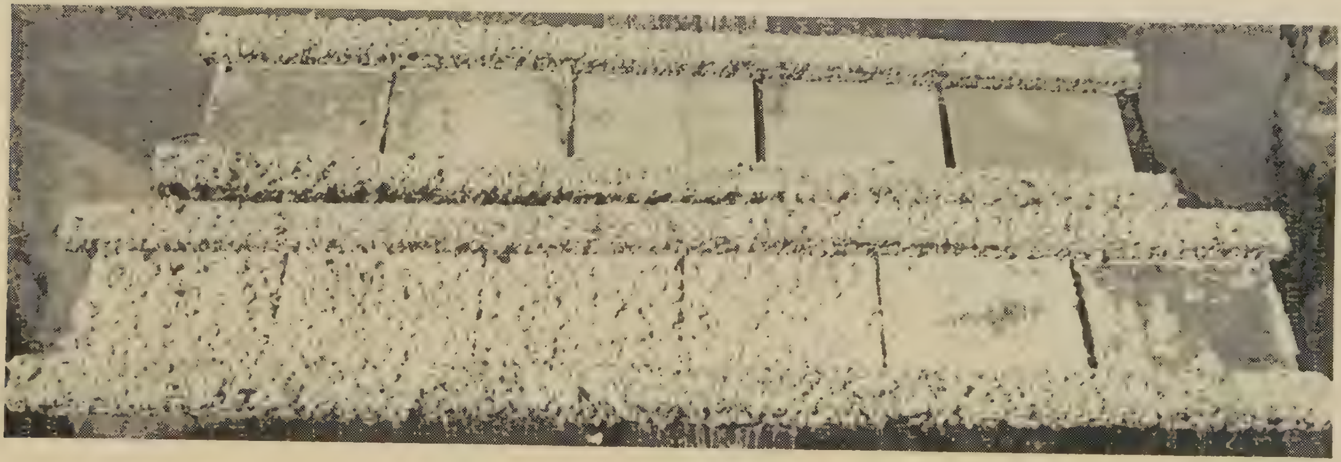

Figure 4. Fouling on Paints Described in Table V, Containing Graded Amounts of Cuprous Oxide, After Four-Month Immersion at Tahiti Beach, Fla.

Paints in the bottom row are Nos. 1–6, in the top row Nos. 7–11, reading from left to right.

experiment although a heavy slime appeared on paints 6, 7, and 8. The copper leaching rates of all the effective paints were greater than 8 micrograms per sq. cm. per day at all times. All of the paints which fouled had leaching rates lower than this at the time of fouling.

Leaching rates were measured on the same paints immersed at Point Reyes for a six-month period. The paints were also exposed at this location on 10 × 12 inch steel panels to determine antifouling performance. The results of these tests were in close agreement with those of Table V. Paints 6–10 were entirely free from fouling growth during the period of test, and at all times maintained a leaching rate greater than 8.2 micrograms of copper per sq. cm. per day. Paints 1–5 fouled badly after one to two months of exposure and had leaching rates lower than 7.5 micrograms per sq. cm. per day at the time fouling occurred.

A series of paints was formulated by substituting various resins on an equal weight basis for the rosin content of the antifouling paint made according to Navy Department Specification 52-P-61. All other components of the specification formula were maintained constant. The unesterified Albertol resins used in these paints were prepared in the laboratory. The WW rosin and ester gum were procured under applicable government specifications; the esterified Albertol (Amberol F-7) and coumarone-indene resin (Neville G) were procured from commercial sources. All paints were prepared on a laboratory three-roll mill.

Leaching rate results on these paints immersed at Woods Hole are listed in Table VI. Paints 4, 5, and 6 became heavily fouled upon exposure at Tahiti Beach, Fla., and Point Reyes. These same paints had low and inadequate leaching rates. Paints 1, 2, and 3 were free from fouling throughout exposure at both locations and had leaching rates in excess of 9.6 micrograms per sq. cm. per day at all times. The adequate amount of cuprous oxide in paints 4, 5, and 6 apparently is not free to dissolve and has no repellent effect on the fouling organisms.

TABLE VI. LEACHING RATES OF SPECIFICATION 52-P-61 TYPE PAINTS FORMULATED WITH VARIOUS RESINS SUBSTITUTED FOR ROSIN

Paint No.	Resin	Leaching Rate, μg. Cu/Sq. Cm./Day, after:						
		0	1 mo.	2 mo.	3 mo.	4 mo.	5 mo.	6 mo.
1	WW rosin	30.0	18.0	16.2	13.5	14.1	16.2	15.8
2	Unesterified Albertol 1	33.3	20.4	17.1	13.8	16.5	18.0	18.8
3	Unesterified Albertol 2	32.1	11.1	10.5	...	9.6	10.8	9.8
4	Ester gum	30.3	3.4[a]	5.5[a]	4.2[a]	2.7[a]	0.9[a]	0.9[a]
5	Esterified Albertol	5.7	0.9[a]	0.0[a]	...	3.3[a]	0.0[a]	...
6	Coumarone-indene	25.6	4.0[a]	2.1[a]	2.1[a]	4.2[a]	...	1.5[a]

[a] Paints which fouled when exposed the indicated time.

A series of paints was formulated by substituting various amounts of Navy Department Specification 52-V-17 phenolic varnish solids for the standard rosin-hydrogenated methyl abietate matrix of Navy Department Specification 52-P-61 antifouling paint. Other components of the specification formula were maintained constant. The paints were prepared on a laboratory three-roll mill.

Leaching rate results on the varnish modified Specification 52-P-61 type paints immersed at Point Reyes are given in Table VII. Paints 1, 2, and 3 maintained leaching rates in excess of 12.1 micrograms per sq. cm. per day at all times and were completely free from fouling throughout the test period at Point Reyes. Paints 4 and 5 had low leaching rates and fouled heavily during the same period.

As a result of these observations and many others, we have concluded that a paint must liberate copper at a rate of about 10 micrograms per sq. cm. per day in order to prevent fouling attachment. Some paints may be effective with leaching rates which occasionally fall slightly below this value (Table V). All paints so far tested which have had leaching rates consistently below this value have become fouled. These statements, however, are limited to paints which depend upon copper or copper compounds as the toxic agent. They are not meant to apply to paints containing mercury compounds or other toxics. Mercury leaching rates have also been measured and have been found to correlate with the effectiveness of mercury-containing paints.

TABLE VII. LEACHING RATES OF SPECIFICATION 52-P-61 TYPE ANTIFOULING PAINTS CONTAINING VARIOUS PROPORTIONS OF PHENOLIC VARNISH SOLIDS

Paint No.	Varnish Solids in Matrix, %	Leaching Rate, µg. Cu/Sq. Cm./Day, after:						
		0	1 mo.	2 mo.	3 mo.	4 mo.	5 mo.	6 mo.
1	0	38.4	21.2	19.3	...	18.6	14.1	15.0
2	10	35.0	18.5	13.1	15.7	16.3	12.9	...
3	20	33.7	15.8	16.3	14.6	13.2	12.1	11.6
4	50	9.0	3.0[a]	5.3[a]	4.2[a]	7.0[a]	4.2[a]	3.1[a]
5	100	2.2	1.3[a]	2.5[a]	0.7[a]	...	...	...

[a] Paints which fouled when exposed the indicated time.

Some paints having poor film characteristics may lose copper in particulate form to the leaching bath. This can result in a high apparent leaching rate which is not a true measure of the effectiveness of the paint, since undissolved copper does not contribute to the toxicity of the surface.

DISCUSSION

It has been shown that the solution of 10 micrograms of copper per sq. cm. of paint surface per day will prevent attachment of all marine growths which normally present a serious ship-bottom fouling problem. Any of these organisms, which include barnacles, annelids, mollusks, hydroids, bryozoa, tunicates, and some species of algae, will attach to paints which consistently maintain lower copper leaching rates. The growth of many microbiological species and some types of algae does not appear to be inhibited by a leaching rate of 10 micrograms per sq. cm. per day, but these organisms are seldom of practical importance in ship-bottom fouling.

The value of 10 micrograms per sq. cm. per day for the minimum adequate leaching rate is lower than that determined by LaQue (*10*) from weight loss measurements of nickel-copper alloy panels. Leaching rate determinations on copper alloys also indicate that some of them may require a higher leaching rate than paints to prevent fouling.

Failure of ineffective copper-base ship-bottom paints to develop adequate leaching rates is usually the result of fundamental errors in formulation. The most common of these are the use of insufficient toxic, as illustrated by the data of Table V, or selection of an unsuitable vehicle, as illustrated by the data of Tables VI and VII. Of course the compound used as the toxic must have an appropriate solubility in sea water in order to leach.

As there are practical limits to the amount of toxic which can be incorporated in a paint film, it is necessary to have an accurately controlled leaching rate to avoid premature exhaustion of the toxic reserve. Young (*19*) first stated the dilemma that the toxic must be soluble and, if soluble, will be washed away, which has discouraged many investigators of the problem ever since. Determination of the rate at which toxic must be liberated permits a more accurate appraisal of the situation. Thus, to maintain a uniform adequate copper leaching rate for one year, a paint film must contain at least 3.6 mg. of copper per sq. cm. of surface area. At a spreading rate of 300 square feet per gallon, this corresponds to a copper content of 2.2 pounds per gallon of paint, a figure well within the limits of practical paint formulation. However, since most effective paints leach at an excessive rate when first exposed and maintain steady-state leaching rates somewhat greater than the minimum adequate value, a fairly large factor of safety as to toxic content must be allowed.

The leaching rate method has proved to be a valuable tool which can be used by the paint technologist in the formulation and testing of antifouling paints. By judicious use of this test a great deal of information upon the characteristics and behavior of antifouling paints can be obtained in the laboratory. It must be stated, however, that the leaching rate test is not presented as a substitute for panel exposures or fouling tests. It is a supplementary tool and has its greatest value when used in conjunction with ship or panel tests. When used in this manner, it serves to eliminate many poor paints in the initial stages, to aid in formulation, and to give insight into the reasons for the failure of various paints. The ultimate evaluation of the effectiveness of antifouling paints will continue to be based on the performance of the formulations on ships in service.

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Contribution No. 336

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THE INFLUENCE OF H-ION CONCENTRATION ON THE MINERAL COMPOSITION OF CHLORELLA PYRENOIDOSA[1]

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ONE FIGURE

The physiological properties of a cell are influenced by the H-ion concentration of the surrounding medium. The nature of the external environment may be an important factor in determining the pH of the cell contents. When plant tisues are obtained from cultures having different mineral composition the pH of the expressed cell sap may show more or less variation (Osterhout, '36; Wadleigh and Shive, '39; Wadleigh and Shive, '39; Hoagland and Broyer, '40). There is evidence that after living cells have been exposed to strong acids, H-ions are set free inside the cell and are slowly removed on returning the cells to their normal environment, and that corresponding phenomena are displayed by bases (Gray, '22). Marked variation in the chemical composition of the protoplast may be expected to result from changes in the amount of free H and OH-ions in the protoplasm. Wadleigh and Shive ('38) have observed a consistent change in the total base content of corn plants as the pH of the nutrient solutions is maintained at different values. There was a definite relation between the potassium content and the pH of the culture solution. Mullins ('42) working on myosin gel in vitro found that the effective binding of potassium was enhanced as the pH values increased up to 8.

These observations suggest that the pH of the substrate may be expected to influence the mineral composition of plant tissues. Accordingly a study was made to determine the changes in the concentration of sodium, potassium, calcium, magnesium, and phosphorus in the cells of Chlorella pyrenoidosa which occur when the pH of the surrounding medium is altered.

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[1] The experiments reported in this paper were conducted in the Biological Laboratories of Harvard University and at the Woods Hole Oceanographic Institution.

Contribution no. 336 Woods Hole Oceanographic Institution.

EXPERIMENTS

Resuspension of Chlorella pyrenoidosa in solutions of potassium-phosphate. "Normal" cells of Chlorella obtained from mass cultures grown in Detmer's medium were resuspended for a period of 1 hour in potassium-phosphate solutions covering a pH range of 5.1 to 10.5. The total concentration of potassium was 0.5 gm. per liter of solution. Resuspension of the cells was facilitated and maintained by the aid of a motor driven stirring device. Finally the material was harvested by centrifuging and analyzed for potassium, calcium, magnesium and phosphorus according to the methods previously described (Scott, '43).

TABLE 1

Concentration of calcium, magnesium, potassium and phosphorus in the cells of Chlorella pyrenoidosa which were washed for 1 hour in solutions of potassium phosphates containing 0.5 gm. of potassium per liter.

WASHING SOLUTION	DETMERS MEDIUM (CONTROL)	POTASSIUM PHOSPHATES			
pH of medium	*6.37*	*5.1*	*5.7*	*8.85*	*10.5*
Ash % dry-weight	8.02	6.00	7.30	8.46	9.45
Ca % dry-weight	1.36	0.43	0.51	0.58	1.03
Mg % dry-weight	0.33	0.31	0.29	0.31	0.31
K % dry-weight	1.41	1.52	1.83	1.86	2.29
P % dry-weight	1.19	0.84	0.87	0.98	1.01
Total base (Ca + Mg + K) % dry-weight	3.10	2.26	2.63	2.75	3.63

The experiment demonstrated a marked effect of the pH of the suspension medium on the total base content of the cells. The pH values are recorded in the top line of table 1 and the total base at the extreme bottom. The influence of pH is most marked in relation to the potassium ion. An increase of pH from 5.05 to 10.5 results in an increase of potassium in the cell from 1.52 to 2.29% dry weight of cells.

Some calcium is lost from the Chlorella obtained from Detmer's medium as a result of washing the cells in the calcium-free phosphate medium, although less is lost in alkaline solutions. Magnesium in the cell remained constant at all pH values. Phosphorus on the other hand shows no consistent relation with total base content of the cells, although less phosphorus was present in the cells suspended in the more acid solutions. These findings are reported in table 1.

Resuspension of Chlorella pyrenoidosa in sodium phosphate solutions. The cells obtained from the same culture as those in the above experiment, were washed in sodium-phosphate solutions covering a pH range of 5.35 to 10.5 for a period of 1 hour. The sodium concentration in all the sodium phosphate solutions was 0.5 gm. per liter. The experiment revealed that at high pH values of the buffered washing solutions, greater amounts of sodium were found within the cells. The uptake of this element, which is indicated in table 2, although slight at low pH, was extremely marked at pH 10.5. The calcium concentration in the cells remained constant except at pH 5.4 where a marked drop was observed. Magnesium underwent a slight decrease at acid pH values. The potassium content of the cells suspended in all cultures containing sodium-phosphate buffers was less than in similar cells resuspended in Detmer's medium or distilled water. Evidently some potassium was lost from the cells which had now absorbed sodium. The greatest addition of sodium occurred at pH 10.5. Phosphorus in the cells increased significantly at alkaline pH values. These observations are recorded in table 2.

TABLE 2

Concentration of calcium, magnesium, sodium, potassium and phosphorus in the cells of Chlorella pyrenoidosa which were washed for 1 hour in solutions of sodium phosphates containing 0.5 gm. of sodium per liter.

WASHING SOLUTION	DETMERS MEDIUM (CONTROL)	DISTILLED WATER	SODIUM PHOSPHATES			
pH of medium	*6.37*	*6.84*	*5.35*	*5.85*	*9.10*	*10.5*
Ash % dry-weight	8.02	6.16	7.65	8.25	8.43	11.97
Ca % dry-weight	1.36	0.74	0.69	1.38	1.26	1.39
Mg % dry-weight	0.33	0.30	0.31	0.31	0.34	0.36
Na % dry-weight	0.00	0.00	0.01	0.02	0.56	2.66
K % dry-weight	1.41	1.22	1.10	0.94	1.04	1.05
P % dry-weight	1.19	0.86	1.08	1.25	1.44	1.66
Total base (Ca + Mg + Na + K) % dry-weight	3.10	2.26	2.11	2.65	3.20	5.46

Addition of 0.01M acid and base to a suspension of Chlorella. The experiment was undertaken to examine the change in pH of a suspension of Chlorella as a result of the addition of known volumes of acid and base. A proportion of cells equivalent to 1 gm. dry weight of algal material were suspended in 200 cc. of phosphate-free Detmer's medium to which were added definite volumes of 0.01M HCl or NaOH. Similar additions of acid and base were made to an identical phosphate-free Detmer's medium containing no algal cells.

The experiment revealed a considerable degree of buffering action by the cells which can best be described by a titration curve. Figure 1 shows the pH of the solutions when definite quantities of 0.01M HCl or NaOH were added to the phosphate-free Detmer's medium containing Chlorella cells, as indicated by the curve labelled medium HCl cells. The curve labeled cells has been corrected for the base bound by an identical cell-free medium which is described by the curve marked medium on figure 1. The buffering action exerted by the cells on the culture medium is especially marked on the alkaline side of neutrality.

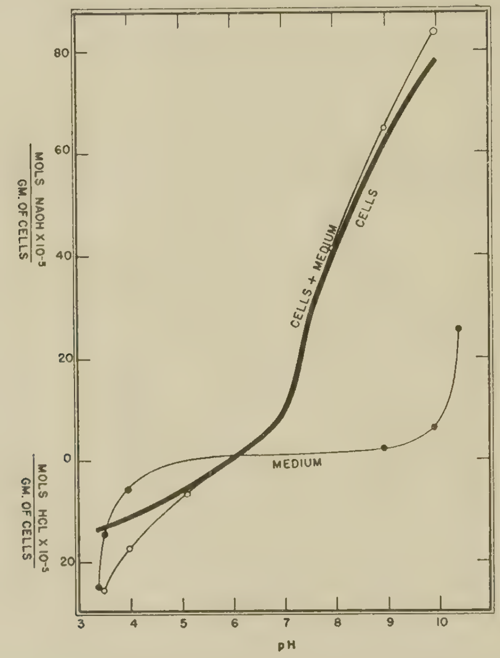

Fig. 1 Titration curve of a culture of Chlorella equivalent to 1 gm. dry-weight of cells indicated by the curve labeled *medium + cells*. The curve labeled *cells* has been corrected for the buffering capacity of an identical cell-free medium which is described by the curve marked *medium*.

After 50×10^{-5} moles of acid or of base per gram dry-weight of cells were added to the suspension the cells were removed from the solutions by centrifuging. The control consisting of a similar suspension of Chlorella to which neither acid nor base had been added was also centrifuged. These three samples were prepared for chemical analysis and determinations made for the sodium, potassium, magnesium and phosphorus content of the cells.

The pH of the suspension of Chlorella in phosphate-free Detmer's medium was 6.37; after addition of 50×10^{-5} moles of hydrochloric acid to a quantity of algae equivalent to 1 gm. dry-weight of cells, the pH of the medium became 3.50. Chemical analysis of the cells, recorded in table 3, revealed a decrease in total base from 3.10 to 1.98% dry-weight of cells. This drop in total base is due to a loss of potassium and calcium from the cells at pH 3.5. It is observed also that approximately 30% of the phosphorus was lost from the cell in the acid medium.

Addition of 50×10^{-5} moles of sodium hydroxide to the medium, on the other hand, resulted in a marked increase of total base of the cells from 3.10 to 4.78% dry-weight. The gain was due to an increase in intra-cellular concentration of potassium and calcium, and to a slight increase of magnesium. The concentration of phosphate at increased alkalinity remained unchanged.

TABLE 3

The mineral composition of Chlorella pyrenoidosa after the addition of 50×10^{-5} moles of HCl and NaOH to a quantity of cells equivalent to 1 gm. dry weight suspended in phosphate-free Detmer's medium.

ADDITION	ACID	NONE	BASE
pH of medium	*3.50*	*6.37*	*9.70*
Ash % dry-weight	4.60	8.02	9.42
Ca % dry-weight	0.55	1.36	2.40
Mg % dry-weight	0.30	0.33	0.47
Na % dry-weight	....	...	0.05
K % dry-weight	1.10	1.41	1.86
P % dry-weight	0.80	1.19	1.22
Total base (Ca + Mg + Na + K) % dry-weight	1.98	3.10	4.78

DISCUSSION

As the pH of the medium surrounding the cells of Chlorella is raised the cation content of the cells increases. This is in agreement with the observations of Wadleigh and Shive ('39), who grew corn plants in culture media of varying hydrogen-ion concentrations and then made determinations on the amount of basic elements present in the tissues.

When Chlorella is suspended in solutions of potassium-phosphates which are more alkaline than Detmer's culture medium the concentration of potassium in the cells is greatly increased although a small amount of calcium is removed from the cell. This lost calcium may represent a partial replacement of calcium by potassium (Scott, '44). At

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Contribution No. 337

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THE MINERAL COMPOSITION OF PHOSPHATE DEFICIENT CELLS OF CHLORELLA PYRENOIDOSA DURING THE RESTORATION OF PHOSPHATE[1]

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TWO FIGURES

There is little information concerning either the chemical composition of unicellular plants grown in deficient media or the recovery of the cells from the deficiencies acquired under such conditions.

The deficiency of certain essential mineral elements, which are normally combined chemically with other intra-cellular constituents may become the limiting factor for synthesis and growth. When the deficient element is restored to the medium, an organism can rapidly absorb the added element and completely recover from the deficiency. Ketchum ('38) demonstrated that phosphorus deficient cells of Chlorella pyrenoidosa can be obtained by letting a culture grow in the light in a medium lacking phosphate. These cells contain one fifth of their normal phosphorus content. The deficiencies thus incurred could be restored by the absorption of phosphate either in the dark or in the light. The phosphate absorbed was directly proportional to the number of cells present and independent of the concentration of phosphate in the medium.

McCalla and Woodford ('38) observed that wheat plants deficient in phosphorus contained less potassium and calcium than are normally present. Consequently, there is a possibility that some of the intracellular cations are joined to organic compounds through the phosphorus atom. Chlorella is a convenient organism on which to determine what elements may enter the cell simultaneously on the restoration of phosphate to phosphate deficient cells.

This paper is a study of the mineral composition of cells of Chlorella which had developed phosphate deficiencies in the dark and in the light, and of the changes in composition which occur as phosphate is restored.

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[1] The experiments reported in this paper were conducted in the Biological Laboratories at Harvard University and at the Woods Hole Oceanographic Institution. (Contribution no. 337, Woods Hole Oceanographic Institution.)

MATERIALS AND METHODS

Cultures of Chlorella pyrenoidosa were prepared according to a modification of the mass culture method of Ketchum and Redfield ('38), for marine diatoms. Cells were allowed to grow in a modification of Detmer's medium containing one fifth of the phosphorus normally present. The modified nutrient medium had the following composition.

Ca $(NO_3)_2$	1.00 gm.
Mg SO_4	0.25 gm.
KCl	0.25 gm.
KH_2 PO_4	0.05 gm.
$FeCl_2$	0.01 gm.

Distilled water to make 1000 cc.

To this medium were added the following minor elements: B 0.5 ppm; Mn 1.0 ppm; Zn 0.05 ppm; Cu 0.05 ppm; Mo 0.05 ppm.

Additional KCl was added to replace the potassium normally present as phosphate in Detmer's medium. After growth had stopped phosphorus was restored to the medium to permit absorption, and after definite time intervals, the cells were harvested and analyzed for phosphorus, potassium, calcium, and magnesium. The analytical methods employed were identical with those previously reported (Scott, '43). The concentrations of the elements in the cell were expressed in milligram-atoms per gram ash-free dry weight of cells. This unit is a useful measure of the relative number of atoms of the respective mineral elements in a fixed amount of plant material.

EXPERIMENTS AND OBSERVATIONS

Chlorella cells which have been placed in a phosphate deficient medium, and have ceased to reproduce because of lack of phosphate, differ in mineral composition from cells not deficient in phosphate in that they contain about one-fifth the normal phosphorus and approximately one-third the normal potassium. The concentration of intra-cellular calcium shows no marked difference, while the magnesium in the cells may be reduced nearly 50% in some cultures.

Restoration of increasing amounts of phosphate to phosphate deficient cells. The experiment was undertaken to determine the uptake of phosphate and accompanying cations while increasing amounts of phosphate are available for restoration.

A 10-liter culture which had stopped growing in the phosphate deficient medium was divided into five parts to which were added 0.00, 0.01, 0.02, 0.03 and 0.04 gm. per liter respectively of KH_2PO_4. After the addition of the phosphate the cultures were kept in the dark for

24 hours; then the cells were centrifuged and analyzed for the mineral elements.

Addition of 0.01 gm. of phosphate per liter of medium did not completely satisfy the requirements of the cells for phosphate, although 0.02 gm. apparently did. Further increase of phosphate in the medium resulted in no additional absorption of this anion by the cells.

Potassium entered the cell simultaneously with the phosphorus in a ration of 1 to 1 atoms. However, the residual ratio in the deficient cells is 2 atoms of potassium to 1 of phosphorus. Evidently there is some potassium in the cell which is bound with phosphorus in the ratio characteristic of the more labile material. The concentrations of calcium and magnesium in the cell, on the other hand, remained nearly constant in all five cultures. These observations are recorded in table 1 and figure 1.

TABLE 1

Concentration of phosphorus, potassium, calcium and magnesium in the cells of Chlorella pyrenoidosa 24 hours after the restoration of increasing amounts of phosphate to a phosphate deficient culture. The data are expressed in milligram-atoms per gram ash-free dry weight of cells.

CULTURE NO.	1	2	3	4	5
Conc. of phosphate in gm./liter of medium	*0.00*	*0.01*	*0.02*	*0.03*	*0.04*
pH of culture	*5.7*	*5.5*	*5.9*	*5.9*	*5.6*
P	0.05	0.10	0.15	0.15	0.55
K	0.10	0.15	0.21	0.20	0.23
Ca	0.24	0.23	0.20	0.19	0.20
Mg	0.09	0.11	0.11	0.12	0.11

Restoration of phosphate to a phosphate deficient culture in the dark and in the light. The experiment was performed in order to compare the absorption of phosphate in the dark and in the light. To a culture of Chlorella pyrenoidosa which had stopped growing because of phosphate deficiency there was added 0.20 gm. of KH_2PO_4 per liter to make up the full complement of phosphate normally present in Detmer's medium. After addition of the phosphate, the culture was divided into two parts, one of which was kept in the dark and the other illuminated by means of neon lights which were equal in intensity to those employed in producing the mother culture. Aliquots of these two cultures were harvested, by centrifuging, at definite time intervals thereafter, and the material was analyzed for phosphorus, potassium, calcium and magnesium.

During the first 27-hour period after restoration of phosphate in the dark, the concentration of phosphorus in the cell underwent a marked increase. In the remaining 63 hours of the experiment no additional phosphate was absorbed. The potassium absorption, which is indicated in table 2 and figure 2, occurred concommitantly with the increase of phosphorus in the cell. The concentration of calcium and magnesium in the cells remained unchanged throughout the period.

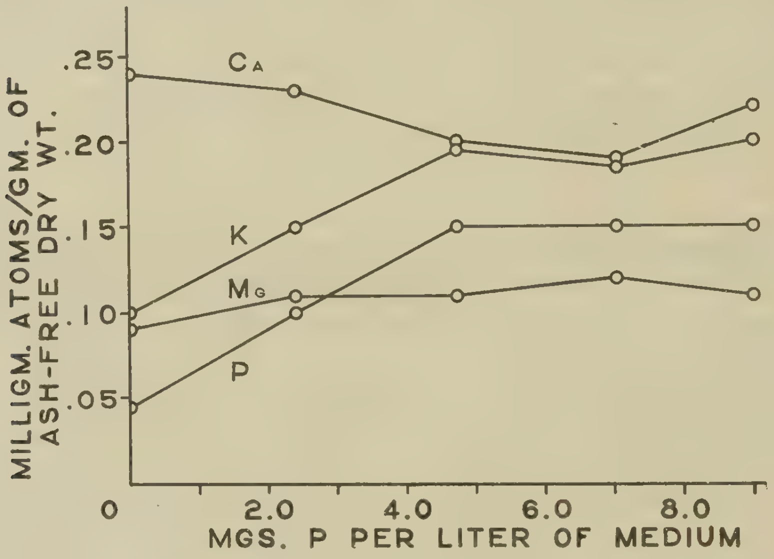

Fig. 1 Mineral composition of cells 24 hours after definite quantities of phosphate added to phosphate-deficient cultures.

TABLE 2

Concentration of phosphorus, potassium, calcium and magnesium in the cells of Chlorella pyrenoidosa kept in the dark after the restoration of phosphate to a phosphate-deficient Detmer's culture medium. The data are expressed in milligram-atoms per gram ash-free dry weight of cells.

TIME IN HRS. AFTER RESTORATION OF P	0	27	48	90
Cell count × 10^6/cc.	36	36	36	36
pH of culture	*6.44*	*6.47*	*6.47*	*6.47*
P	0.03	0.14	0.14	0.14
K	0.08	0.15	0.16	0.16
Ca	0.20	0.21	0.21	0.22
Mg	0.06	0.05	0.06	0.05

After phosphate was restored to the culture placed in the light, the phosphorus concentration in the cells, recorded in table 3 and figure 2,

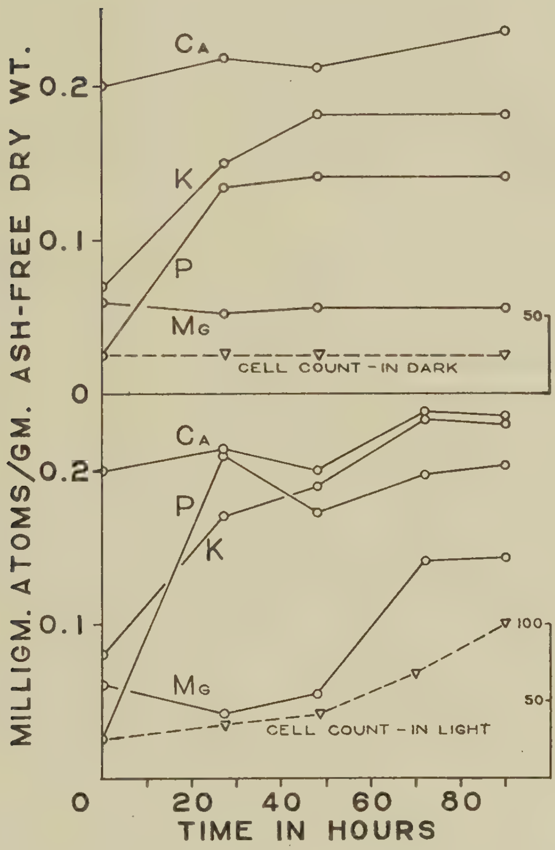

Fig. 2 Mineral composition of cells at definite time intervals after restoration of phosphate to a phosphate-deficient culture.

TABLE 3

Concentration of phosphorus, potassium, calcium and magnesium in the cells of Chlorella pyrenoidosa kept in the light after the restoration of phosphate to a phosphate-deficient Detmer's culture medium. The data are expressed in milligram-atoms per gram ash-free dry weight of cells.

TIME IN HRS. AFTER RESTORATION OF P	0	27	48	72	96	240
Cell count × 10^6/cc.	36	36	44	68	90.0	90.0
pH of culture	*6.44*	*6.54*	*6.50*	*6.53*	*6.70*	*6.90*
P	0.03	0.21	0.17	0.20	0.20	0.28
K	0.08	0.17	0.19	0.24	0.23	0.29
Ca	0.20	0.21	0.20	0.23	0.24	0.26
Mg	0.06	0.04	0.05	0.14	0.14	0.17

underwent a marked increase during the first 27-hour period of the experiment. Within the next observation period of 48 hours, growth of the culture was observed to begin. The cell count of the cultures at time intervals after the restoration of phosphate is indicated in the second line of table 3. During the first part of the growth period, the phosphorus content declined slightly, but at 72 hours had returned to a constant value which was maintained throughout the period of exponential growth (fig. 2).

After the restoration of phosphate to the culture kept in the light, potassium was absorbed concomitantly with the phosphate in a ratio of 1 atom of potassium to 2 atoms of phosphorus. After growth had commenced, however, the ratio became 1 to 1 atom. The amount of magnesium in the cell underwent a marked increase during the end phase of exponential growth, although the phosphorus remained constant during this period.

When the culture was allowed to remain 10 days in the phosphate medium after it had reached its maximum cell count, a marked increase was observed in the concentration of phosphorus and all three cations.

Information from unpublished experiments reveals that when the exponential cell-reproduction period is over, the volume of the cells increases and no autospores are observed within them. During this period light has become the limiting factor for photosynthesis. According to Pearsall and Loose ('40), after Chlorella vulgaris reaches a maximum cell count the ratio of insoluble to soluble carbohydrates in the cells increases. This phenomenon occurs at the same time and under the same conditions as the increase in phosphorus observed in Chlorella pyrenoidosa.

DISCUSSION

The absorption of phosphate, either in the dark or in the light, does not depend on the amount of phosphate in the medium except at limiting concentrations where there is inadequate phosphate to supply the amount normally required by the cell. The results of the second experiment indicate that after a phosphate deficient culture, to which phosphate has been restored, is placed in the light, more phosphorus is found within the cells than is present in cells from a similar culture kept in the dark. Evidently phosphate is combining with intra-cellular constituents, which as Ketchum ('39) suggests, are produced in photosynthesis.

Potassium is the only cation whose intra-cellular concentration appears definitely to be related to the amount of phosphorus in the cell. Since the culture medium employed in these experiments contained the normal content of potassium as prescribed by Detmer's formula, and because the concentration of potassium in the cell is independent of the amount of potassium in the medium except at extremely low levels of potassium (Scott, '43, '44), it is obvious that we are dealing not with the effect of the external potassium concentration, but with an actual relation in which the amount of potassium in the protoplasm depends on the amount of phosphate absorbed by the cell. Apparently, in the Chlorella cell, potassium is an element associated with phosphorus in chemical union with cellular constituents produced in photosynthesis. These two elements are absorbed by the cell either in the dark or light in an approximate ratio of one to one atoms although the absorption ratio during the first stages of phosphate restoration by phosphate deficient cells is in favor of a greater proportion of phosphorus. The delay in the absorption of potassium relative to phosphorus suggests that the phosphorus compounds must be formed before the potassium is absorbed.

The absorption of calcium by the cell of Chlorella is not likewise related directly to the phosphorus content of the cell. This observation is in agreement with Elmendorf and Pierce ('40) who found that the ratio of calcium to phosphorus absorbed by vegetable tissues fluctuated between rather wide limits as a result of varying the mineral element content of inorganic soil fertilizers.

The increased concentration of magnesium, which occurs after cells have been in the light for 24 or more hours after phosphate restoration, is probably associated with the synthesis of chlorophylls.

SUMMARY

1. Mass cultures of phosphate deficient cells were prepared by allowing cells of Chlorella pyrenoidosa to grow in a phosphate deficient medium.

2. The phosphate absorbed by phosphate deficient cells either in the light or in the dark is independent of the concentration of phosphorus in the medium except at the limiting concentrations of phosphate normally required by the cell.

3. The amount of potassium absorbed depends on the amount of phosphorus taken in by the cells.

4. The absorption ratio of potassium and phosphorus in the light or dark is approximately one to one atoms.

5. It is assumed that phosphorus and potassium combine chemically with some constituent in the cell produced by photosynthesis.

6. Calcium and magnesium are not absorbed concomitantly with phosphorus by phosphate deficient cells.

7. After the exponential growth phase is over, there is an increase in the concentration of phosphorus, potassium, calcium, and magnesium in the cell.

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Contribution No. 338

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VERTICAL DISTRIBUTION OF PELAGIC FORAMINIFERA.*

FRED B. PHLEGER, Jr.

ABSTRACT. The importance of additional knowledge of the ecology of pelagic Foraminifera is stressed. Methods for quantitative collections and study of pelagic Foraminifera are discussed. Study of five serial plankton tows indicates that living Foraminifera are present in significant quantities down to a depth of at least 1,000 meters.

STUDY of submarine cores has shown the necessity of more accurate knowledge of the ecology of Foraminifera. The most fundamental problem is the question of where the animals live during all or part of their existence. It is known that certain species are pelagic, because they have been collected in plankton tows, and it is assumed that all others are benthonic.

Most geologists have subconsciously assumed that all pelagic Foraminifera live at the surface of the sea. This does not appear logical since other elements of the plankton live throughout the water column. It is true, however, that the greatest abundance of plankton occurs in the surface water layers. In addition, certain distributions of benthonic Foraminifera in submarine cores are difficult to explain if we assume that they are strictly benthonic.

There are other aspects of the problem of distribution of pelagic species. Do the shells in marine bottom samples represent an assemblage which lived in the water directly above the position of the sample? How far are the shells transported by currents before deposition? In interpreting past marine environments by faunas in submarine cores, it is essential to know what water layers are being interpreted. Most of the work done on submarine cores has been a study of the different marine environments represented by the deposits at different levels in many cores. The recognition of environmental differences in the sediments which occur in the cores is based almost entirely on different occurrences of Foraminifera at different stratigraphic levels. Most of the differences between faunas occurring at different core levels can be interpreted as due to water temperature or climatic variations. Many of the Foraminifera used for these relative temperature determinations are pelagic.

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* Contribution No. 338. Woods Hole Oceanographic Institution.

If all the pelagic forms normally live at or near the surface of the sea, the problem of interpretation is a simple one, but the greater the vertical distribution of the pelagic Foraminifera, the more complex the problem. In ocean water of warm temperate regions there is a decrease in temperature with depth. Moreover, the layers of water above about 100 meters depth have a much greater annual range of temperature than deeper water. This is shown graphically in Fig. 1, which contains generalized minimum and maximum temperature curves for the water of the continental slope off eastern North America. Any foraminifer which lives at 500 meters depth must have a different temperature tolerance (8-10° C.) than one which is restricted to the surface (12-26° C.) (See Fig. 1).

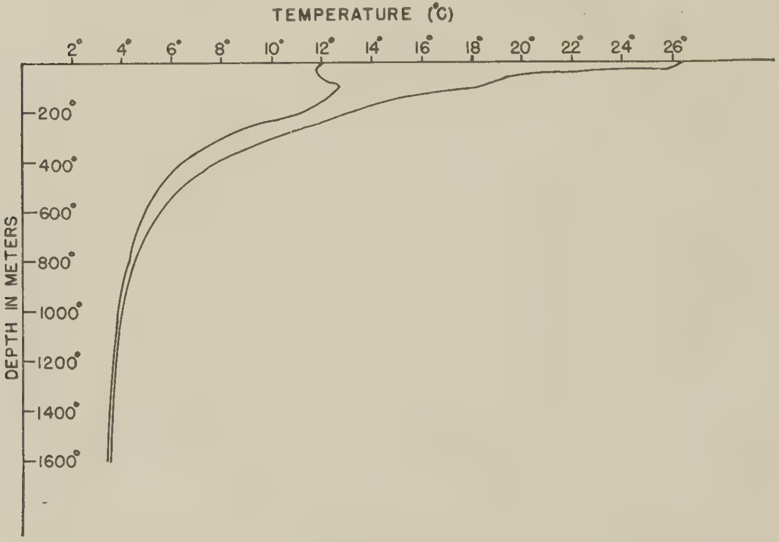

Fig. 1. Minimum and maximum temperature profiles for the continental slope water off eastern North American. (Modified after Iselin.)

This paper is in the nature of a report on methods which have been developed for attacking the problem of bathymetric distribution of Foraminifera. The data obtained from the plankton tows made by the writer are inadequate, but they illustrate the procedure and may be indicative of the type of results to be expected in future investigations.

Any study of the distribution of pelagic Foraminifera should be made from tows taken at known water depths and should be quantitative if it is to be of any value in solving the problems relative to ecology and paleoecology. Most records of tows are purely qualitative and are from surface water zones. One of the recent exceptions is the work done aboard the *Meteor* in equatorial Atlantic waters, reported by Schott (1935).[1] A series of traverses were made between the African coast and Brazil. In the report of the Meteor Expedition, Schott lists plankton tow records for Foraminifera from 93 stations. The tows were made with a Nansen closing net, and the water was sampled at various depths down to 1000 meters. The tows were of uniform time duration and the total number of specimens of Foraminifera in each sample were counted, with percentage ratios of the species also listed. In this region the greatest frequency of pelagic Foraminifera is in water depths of 0 to 100 meters, although significant numbers occur at all depths sampled. The following is an analysis of Schott's data by the writer, and it clearly shows this.

Depth in Meters	No. of Tows	Mean No. of Specimens per Tow
0–100	71	489
100–200	7	8
200–400	13	24
400–600	19	10
600–800	12	11
800–1000	19	28

Globigerinoides sacculifera is the most abundant species in the Atlantic equatorial region. *Globigerina bulloides* and G. *inflata* are found in abundance only in the colder surface waters of this equatorial region or in the colder water at considerable depth.

The quantitative results of these tows are only partially reliable, as Schott realized. The reliability of the results showing the mean numbers of specimens occurring at different depths is directly proportional to the number of tows. A difficulty inherent in the Nansen closing net is that the volume of water strained is unknown. Great variation in volume strained is common, as illustrated by quantitative plankton samplers now in use. No attempt was made to discover which specimens were alive when collected and which were simply empty shells. The empty shells represent specimens which are sinking to the bottom and are of no significance in solving problems of habitat.

During a short cruise of the *Atlantis* in the summer of 1941, the writer made serial plankton tows at known depths to 1000 meters. These were made with the quantitative sampler developed by Dr. George L. Clarke and Mr. Dean F. Bumpus (1940)[2] of the Woods Hole Oceanographic Institution. This device may be opened and closed at known depths, and in addition, the volume of water strained is measured by the revolutions of a propeller. The plankton was preserved successfully in neutral formalin; adequate neutral formalin may be made by addition of sodium carbonate to the solution. Formalin which is not neutralized will, in many cases, dissolve the tests of Foraminifera. The use of alcohol as a preservative is not recommended since it makes a white gelatinous precipitate with sea water, and it is difficult to see and to disengage Foraminifera from the other plankton.

In operating these plankton nets for pelagic Foraminifera, certain precautions must be observed, since the small size and relative abundance of the specimens may cause inadvertent contamination from material on board ship or in water layers not being sampled. The nets must be kept in a clean container or hanging, and contact with other things on board avoided. When the nets are recovered after a tow has been made, they should be thoroughly washed on the outside with fresh water or filtered sea water. After recovering the plankton from the net, which is done by repeated washing into a bottle fastened to the end, the net should be cleaned with a stiff spray of water for several minutes.

In order to study the Foraminifera it is necessary to separate them from the remainder of the plankton, of which they may constitute only a fraction of one per cent. This may be done by extracting each specimen with a pipette, and this procedure avoids injury to delicate specimens. Each plankton sample must be thoroughly examined several times, since small specimens tend to be obscured by other plankton materials.

One of the difficulties has been to distinguish living specimens from empty tests. This involves recognition of protoplasm in the specimen and is very difficult without staining. Certain biological stains can be applied, but decalcification of the specimens is advisable and in most cases necessary. This procedure destroys the test which is most valuable for a paleontologist and upon which the recognition of the species is based. At the suggestion of Dr. George P. Child of the Amherst College Biology Department, a successful technique for recognizing protoplasm without dissolving the test was developed by Mr.

Garrish Metcalf, a student at Amherst College. This is the Biuret test for protein in which the protein-containing substance such as any protoplasm is colored purple.

The procedure in making the Biuret test on this material is as follows: Foraminifera in formalin solution are placed in a shallow glass evaporating dish and to this a few drops of a 10 per cent solution of sodium hydroxide are added. The sodium hydroxide breaks down the proteins in the protoplasm to form compounds related to urea. After several minutes (in the experience of the writer approximately 30 to 40 minutes) a few drops of a very dilute solution (.05 per cent) of copper sulphate is added. In a short time the protoplasm is colored purple and this coloration can be seen clearly through the test against a white background with a properly adjusted light source. If the specimens are to be stored for future reference, it is necessary to wash them several times before storing, since the sodium hydroxide eventually will destroy the tests. The entire technique is simple, speedy, and the shells can be preserved for future reference.

This method can be used to great advantage in studying benthonic populations. Any marine bottom sample probably contains more empty tests than live Foraminifera. It is necessary to know which specimens were living at the time the sample was taken to determine: 1.) which species actually live in that environment and were therefore not transported there, and 2.) the productivity of the area and therefore the probable rate of accumulation of the tests. Also, there is some evidence that certain pelagic species may live a part of their life cycle at or near the bottom. Many empty tests of Foraminifera become filled with clayey substances on marine bottoms. These materials have an appearance not unlike protoplasm after being placed in a preserving solution. Ordinary biological stains affect this substance in almost the same way as they do protoplasm, and so cannot be used to differentiate living from dead specimens. The Biuret test is a successful method for distinguishing those individuals filled with protoplasm.

The greatest concentration of pelagic specimens is in water over the continental slope and ocean basins, according to occurrences in bottom samples. The 1941 *Atlantis* tows came from the basin of the North Atlantic, south of Georges Bank, where the depth of water varies from about 3000 to 5000 meters. The tows were made primarily to discover if the

FIGURE 2. Distribution of Foraminifera in Plankton Tows.

	Station 1 Lat. 40° 05′ N Long. 68° 21′ W			Station 2 Lat. 39° 50′ N Long. 67° 11′ W			Station 3 Lat. 40° 58′ N Long. 66° 39′ W		Station 4 Lat. 40° 43′ N Long. 69° 50′ W			Station 6 Lat. 39° 55′ N Long. 68° 48′ W		
	Sample 1 Depth 700 m. Vol. 26.04 cu. m.	Sample 2 Dep.h 350 M. Vol. 12.53 cu. m.	Sample 3 Depth 70 m. Vol. 6.13 cu. m.	Sample 1 Depth 1000 m. Vol. 5.14 cu. m.	Sample 2 Depth 650 m. Vol. 11.92 cu. m.	Sample 3 Depth 400 m. Vol. 4.91 cu. m.	Sample 1 Depth 700 m. Vol. 35.44 cu. m.	Sample 2 Depth 325 m. Vol. 20.6 cu. m.	Sample 1 Depth 975 m. Vol. 17.73 cu. m.	Sample 2 Depth 475 m. Vol. 17.61 cu. m.	Sample 3 Depth 75 m. Vol. 17.51 cu. m.	Sample 1 Depth 1000 m. Vol. 28.36 cu. m.	Sample 2 Depth 500 m. Vol. 18.4 cu. m.	Sample 3 Depth 100 m. Vol. 19.84 cu. m.
Globigerina *bulloides*	1*(5)*	*(1)*	*(10)*	2*(2)*	*(11)*	9*(18)*	58*(70)*	*(8)*	72*(56)*	2	16*(13)*	12*(34)*	*(1)*	6*(1)*
G. inflata				*(2)*		*(3)*	1							
G. pachyderma									2					
Globigerinoides *rubra*	1*(3)*		5*(9)*	4*(4)*	*(11)*	4*(9)*	5*(8)*		8(8)		2	1*(7)*		1
G. truncatulinoides				*(1)*	*(1)*		*(1)*							
Globigerinella *aequilateris*				*(2)*	*(1)*									
Unidentified Globigerinidae							8							
Globorotalia *scitula*						*(1)*		*(1)*						
G. hirsuta						*(2)*								
Orbulina universa							1							

The numbers in light type indicate living specimens and the numbers in italics and in parentheses indicate empty tests.

quantitative samplers could be operated successfully at great depths and whether Foraminifera occurred at depths in this region and could be collected. An equally important purpose was to use the material for experiments in the technique of preservation and study.

Since only six serial tows were made (and the material in one tow was destroyed in the process of experimentation) the results have no quantitative significance. It is possible, however, to make several interesting and important observations on the data obtained. The most significant fact is that specimens of Foraminifera were present in every sample collected at several depths from 75 m. to 1000 m. The number of living specimens found at 1000 m. varied from 1.5 specimens to 4.6 specimens per cu. m. of water. At station 4, approximately four and one-half times the number of living specimens per unit volume of water were found at 975 m. as were found at 75 m. It is true that most of the specimens found in most of the deep tows were empty tests, presumably those settling from the upper layer of water. The data suggest a larger population of living Foraminifera at about 1000 m. than at about 100 m. at some localities.

Nearly all the specimens in the tows are very small and without exception very thin shelled. This may have been due to the season of year at which collecting was done (August). In bottom samples from the same region a large percentage of the specimens are large and heavy-shelled. By far the greatest number of living and dead specimens were of *Globigerina bulloides* with *Globigerinoides rubra* occurring in significant numbers.

This is preliminary to a more extensive program of towing for pelagic Foraminifera which, it is hoped, can be undertaken as soon as conditions permit. It is further hoped that other individuals and organizations will undertake similar studies, either in the North Atlantic or elsewhere, and that similar studies will be made on benthonic populations.

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15157

Occurrence of Thiaminase in Marine Teleosts.*

WARREN H. YUDKIN. (Introduced by C. N. H. Long.)
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Diets containing whole raw carp have been found to be responsible for deaths due to B_1 avitaminosis in silver foxes.[1,2] Available thiamine was rendered inactive by the raw carp while still in the feed mixture.[3] This destruction of thiamine has been shown to be a split of the molecule into its pyrimidine and thiazole portions; the split is catalyzed by an enzyme, thiaminase, present in the viscera of raw carp and soluble in 10% salt solution.[4,5]

Deutsch and Hasler[6] examined a total of 31 species of fresh-water fish in the Great Lakes region and found the thiaminase to occur in about half of them. Examination by these authors of 9 marine teleosts, however, did not reveal thiaminase in any. They determined the presence of the enzyme in fish homogenates by their power to destroy the thiamine of added brewer's yeast. Thiamine analyses were made by the thiochrome method.

The only marine teleost which has been demonstrated to contain thiaminase is the Atlantic herring, *Clupea harengus*.[7] Both feeding tests and incubation with thiamine have given ample proof of the high thiaminase activity of this fish.[7,8,9] Green *et al.*,[10] on the basis of observations on the effect of diets fed at fur farms, suggest that Atlantic whiting, *Merluccius bilinearis,* has the power to destroy thiamine. On the other hand, according to the assays of Deutsch and Hasler[6] the whiting contains no thiaminase.

Large portions of the catch in certain fisheries are usually discarded,[11] although in recent years there has been a decided trend towards fuller utilization of this material. The possibility exists that such occasionally marketable or unmarketable (*i.e.*, "trash") species may at times be used for livestock feed on coastal farms. The presence of thiaminase in such species would preclude their use if raw and unprocessed. This paper reports the results of assays for thiaminase in 4 species of marine teleosts, namely:

Merluccius bilinearis; whiting
Prionotus carolinus; sea robin
Tautogolabrus adspersus; cunner
Tautoga onita; tautog or blackfish.

Thiaminase activity was determined by the method used by Sealock *et al.*[5] The viscera of fresh fish were minced in a Waring blendor with an equal volume of 10% saline in 0.1M phosphate buffer at pH 7.4. Large particles were spun down by centrifugation and 2 ml of the supernatant suspension (equivalent to about 1 g of fish) was transferred to a centrifuge tube together with 750 γ of thiamine hydrochloride and 1 ml of a 0.2M phosphate buffer at pH 7.4. The contents of each tube were adjusted to a volume of 5 ml with distilled water and then incubated for 2 hours at 37.5°. At the end of incubation 5 ml of 20% trichloracetic acid were added and the protein allowed to flocculate with subsequent centrifugation. Standards received the same ingredients as the experimental tubes but the trichloracetic acid was added directly after the thiamine and incubation was omitted. Controls were run with the fish suspension subjected to 100° for 20 minutes prior to the addition of the thiamine followed by incubation. For assay two 4 ml samples of the resulting supernatant were used. A simplified modification[12] of the Melnick and Field[13] colorimetric diazonium method was employed to determine residual thiamine. It was found that the zeolite adsorption could be omitted without interference of color formation leading to erroneous analyses providing the absorption of light by the xylene extract was measured in a Klett-Duboscq visual colorimeter.

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* Contribution No. 339 from the Woods Hole Oceanographic Institution.

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None of the 4 species of marine teleosts tested showed the presence of thiaminase in a saline suspension of its minced viscera. A similar suspension of whole minced quahogs (*Venus mercenaria*), which has already been shown to contain thiaminase,[9] destroyed 33% of the added thiamine in 2 hours. No appreciable heat-destruction of thiamine was found to occur under the conditions of the incubation.

The absence of thiaminase in most marine teleosts is still inexplicable. In the 13 species so far investigated only the herring, *Clupea harengus*, has been demonstrated to contain the enzyme. The conclusion of Deutsch and Hasler[6] that the whiting does not contain thiaminase has been confirmed. In their experiments with cod and haddock, Deutsch and Hasler[6] used eviscerated fish. Since the enzyme occurs primarily in the viscera, if at all, this leaves the status of these fish doubtful. Explanation of the occurrence of thiaminase in some fish and not in others may rest on a phylogenetic basis as has been suggested.[6] In that case extensive investigation of additional marine fish as well as freshwater, estuarine, and marine invertebrates and primitive chordates is requisite.

Summary. In 4 species of marine teleosts no thiaminase was found according to the procedure described. This brings to a total of 12 the marine teleosts in which there appears to be no thiaminase. In only one species, the Atlantic herring, has its presence been demonstrated.

I wish to thank Captain Jared Vincent for supplying me with the Atlantic whiting used in this investigation.

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Observations on the Comparative Ecology and Life History of Two Sea Robins, *Prionotus carolinus* and *Prionotus evolans strigatus*[1]

By Nelson Marshall

Introduction

TWO main incentives underlie this study. One stems from the desirability of learning more about marine food resources, especially since recent food shortages have made us more conscious of hitherto little used palatable fishes such as these sea robins. Included in this paper are data on weight-length relationships, abundance of size groups, relative abundance and other pertinent life history facts concerning *Prionotus carolinus* and *Prionotus evolans strigatus*. With such records, taken when these fish are not subject to an intensive fishery, the biologist will be able to make more intelligent analyses of the effects of fishing effort, if and when these species are taken in large numbers. Such an approach to possible fisheries problems of the future, recommended by many far-sighted biologists, is impractical unless research efforts are concentrated on those species which show some likelihood of utilization. The marketing of these sea robins has never been great,[2] many simply being used as bait when taken, but should these two species once meet with favor on the market, they could be taken in great numbers as an outstanding element (now being discarded as trash) of the pound net and inshore trawler catches. The enthusiastic recommendations of many who have tasted sea robins make it seem probable that trends toward broadening our current limited marketing of sea foods will encourage the utilization of this unexploited resource.

Another incentive issues from the desire to compare two such similar species inhabiting the same region. These two fishes, *Prionotus carolinus* and *Prionotus evolans strigatus*, are abundant during spring, summer, and early fall months in coastal waters off southern New England and the middle Atlantic states, no other triglids being common to this region. Their distribution, discussed by Jordan and Evermann (1898), Bigelow and Welsh (1925), Nichols and Breder (1927), Hildebrand and Schroeder (1928), and others, is such that they are found only in small numbers to the north of Cape Cod and extend southward as far as the coastal waters of South Carolina, the population of *P. evolans* off the Carolina coasts being referred to as

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[1] Contribution No. 341 from the Woods Hole Oceanographic Institution.

[2] Market statistics on sea robins [*P. carolinus* and *P. evolans strigatus*] have been made available through the courtesy of A. W. Anderson of the U.S. Fish and Wildlife Service. The total sold annually over a period of twelve years have been:

1931	234,417 lbs.	1938	461,000 lbs.
1932	148,466 lbs.	1939	404,400 lbs.
1933	132,040 lbs.	1940	314,500 lbs.
1937	254,900 lbs.	1942	262,400 lbs.

Records are incomplete for the years omitted and have not as yet been compiled for the years subsequent to 1942. The following list of landings by vessels at New York City suggests a recent increase in marketing these species:

1938	6,005 lbs.	1942	1,495 lbs.
1939	19,475 lbs.	1943	5,035 lbs.
1940	14,615 lbs.	1944	28,315 lbs.
1941	10,850 lbs.		

a distinct subspecies, *P. evolans evolans*.[3]

To distinguish between these two species of sea robins of the New England and middle Atlantic coastal waters the following characters may be used:

P. carolinus
- Pectoral fin reaches back to about sixth ray of second dorsal
- Margin of caudal fin concave
- Body and fins nearly plain except for some dark mottlings, chin usually dark

P. evolans strigatus
- Pectoral fin reaches back to ninth or tenth ray of second dorsal
- Margin of caudal fin almost straight
- Two dark longitudinal stripes conspicuous along each side of body
- General background color modified by orange tinge, particularly toward ventral surface and on pectoral fins

Common names applied to these species are important in introducing this study. Both are commonly referred to simply as sea robins, for few fishermen, commercial or otherwise, bother to differentiate between them. The Committee on the Common and Scientific Names of Fishes of the American Fisheries Society has settled on the following (as learned through correspondence with committee chairman Walter H. Chute in 1944):

Prionotus carolinus—Common sea robin

Prionotus strigatus [*P. evolans strigatus*]—Northern striped sea robin. The latter form is also commonly spoken of as the red (sea) robin and even as the cock or male robin on the erroneous assumption that it is the male and *P. carolinus* is the female of the same species.

Seasonal Occurrence in Southern New England Waters

With respect to their seasonal distribution *Prionotus carolinus* and *P. evolans strigatus*, like many other species of the region, are common along southern New England and Long Island shores during the warmer spring and summer months but leave this vicinity during the fall. Bigelow and Welsh (1925) state that *P. carolinus* leaves the southern New England coast in October and reappears in late April or May. This is confirmed and also shown to apply to *P. evolans strigatus* by records kept by the Bingham Oceanographic Laboratory in catch analyses that involved taking monthly trips on a flounder dragger fishing near Block Island, Rhode Island. In this sampling the first catch of *P. carolinus* in 1943 was from the trip made April 22; in 1944 from the trip on May 18. The first catch of *P. evolans strigatus* in 1943 was from the trip on May 11, and in 1944 from the trip on May 18. The last catch of *P. carolinus* during the 1943 and 1944 seasons was on the trips of October 31 and October 26 respectively; while the last catch of *P. evolans strigatus* was on September 21 in 1943, and October 26 in 1944. Temperature records obtained from lightships stationed in the shallow coastal waters off southern New England have been collected and summarized by Parr (1933) and from these it is seen that *Prionotus* is entering the region when the water temperatures range slightly above 40° F., is leaving at temperatures a little below 60° F.

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[3] Jordan and Hughes (1887) suggested that the fish from northern localities, described as *P. strigatus*, and the closely related populations from southern localities, described as *P. evolans*, might be subspecifically related. Without comment Fowler (1906) put this suggestion into practice by referring to *P. evolans strigatus* in his "Fishes of New Jersey". Though the adoption of this nomenclature has been widespread, for example by Breder (1929), it has not been universally accepted and the true relationships of these populations have not been carefully studied.

The arrival of these species in the spring results in their occurrence in very large numbers in the pound nets. Norman G. Benson, who operates a pound net in Lambert's Cove, Vineyard Sound, Massachusetts, sent me the following note in May, 1944: "I put in trap the 29th of April. First haul May 1st—about 30 bbls. of robins [undoubtedly the majority were *P. carolinus*] which kept up for about 10 days." This quotation typifies the experience that pound and trap net operators have during this season not only with sea robins but with other species having a similar seasonal distribution.

The above mentioned trawler analyses of the Bingham Oceanographic Laboratory, which effectively date the beginning and end of seasonal inshore abundance of *P. carolinus* and *P. evolans strigatus* in southern New England, fail to show either species in any numbers during midsummer months. But the hauls studied were taken in about 18 fathoms while the reports of commercial fishermen and my own experience dragging in less than 10 fathoms in the Woods Hole area clearly demonstrate their continued abundance in shallower waters during this period.

The year around presence of *P. carolinus* in Chesapeake Bay described by Hildebrand and Schroeder (1928) is quite different from its seasonal distribution in New England. Chesapeake Bay waters are shallow and 23 fathoms is the greatest depth from which *P. carolinus* was recorded by these authors. Using temperature records from the tide station at Solomon Island, Maryland, a mid-bay station at the mouth of the Patuxent River, it is seen that the mean February (coldest month) water temperature from the years 1938 through 1942 was 38° F; consequently there is little doubt that in these shallow waters *P. carolinus* are exposed to lower temperatures than are prevalent in the southern New England coastal waters at the time of their departure. In discussing this matter, Mr. Schroeder has suggested that fish of this sort may be somewhat passive in their migration tendencies and thus might not undertake the long range travel necessary to leave the Chesapeake Bay waters.

Relative Abundance

Available information from which a concept of relative abundance might be developed comes from two chief sources, commercial pound net catches and catch records from commercial and research otter trawl operations.

Repeated sampling from June 11 through September 6, 1943, of the catch of five pound nets located in Buzzards Bay and Vineyard Sound, Massachusetts, yielded a count of 659 *P. carolinus* to 262 *P. evolans strigatus*, or a ratio of 2.5:1. These data, though not extensive, are in general agreement with relative catches as described by commercial pound net fishermen with years of experience. The somewhat greater numbers of *P. carolinus* can be regarded, therefore, as the general trend for pound net catches provided it is realized that there are times and places when such a ratio will be markedly upset. For example, on July 23, 1943, fishermen who had hauled five pound nets off Fire Island Inlet, Long Island, brought in for commercial sale only 94 *P. carolinus* to 323 *P. evolans strigatus*, a ratio of 1:3.4, which is only partially explained on the basis that the latter species reaches commercial size at an earlier age (see section on age and rate of growth).

In marked contrast to the catches of these five pound nets, a commercial dragger operating an otter trawl off Fire Island on the same date got a much larger catch of *Prionotus* in a ratio of 19 *P. carolinus* to 1 *P. evolans strigatus*. A similar contrast is noted when comparing the catches of two pound nets located in Menemsha Bight, Vineyard Sound, Massachusetts, on July 28, 1943, with otter trawl catches (using the fine meshed shrimp trawl described below) made in the same region August 2, 1943. The former yielded 81 *P. carolinus* to 67 *P. evolans strigatus,* or a ratio of 1.2:1; the latter yielded 94 *P. carolinus* but not a single *P. evolans strigatus* although trawling operations were carried out in all parts of the Bight, including areas in the immediate vicinity of pound nets. This comparative scarcity of *P. evolans strigatus* in otter trawl catches has been established by many additional records in 1943 and 1944. It also agrees with the accounts of fishermen who have been using this type of gear.[4]

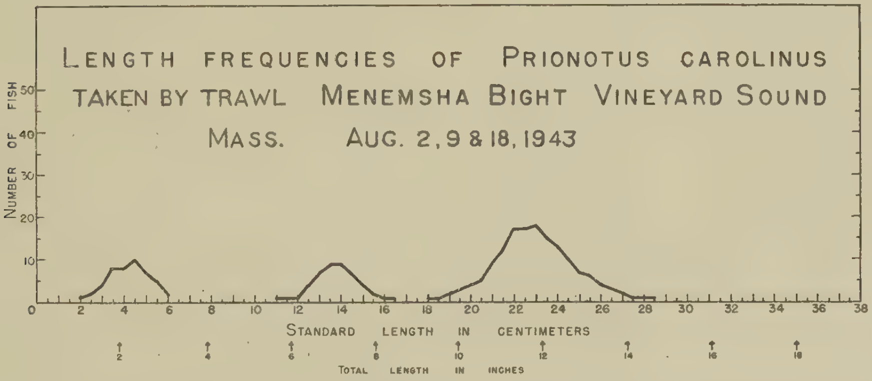

Fig. 1. Length–frequency distribution of *Prionotus carolinus* taken by shrimp trawl in less than 12 fathoms in Menemsha Bight, Vineyard Sound, Mass., August 2, 9, and 18, 1943. Data smoothed by threes except where smoothing would eliminate the record of a single specimen of a given length.

An interpretation of the contrast in species abundance between pound net and otter trawl catches issues from a consideration of their respective modes of operation. The pound net is limited to the shallow water in which it must be set and depends on the movement of fish along the shore in such a way they will be guided into the heart and pound by the leader. Owing possibly to the large mesh of the gear (that of the pound being about 2½ inches stretched measure with the rest proportionately larger), some of the younger, smaller fish are not taken, a factor which might tend to exaggerate

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[4] The sex ratio of *P. carolinus,* judged from sampling records summarized in the following table, is approximately 1 to 1 and seems to be the same in pound nets and trawl catches.

	Males	Females
Pound net catches Woods Hole area 1943	260	280
Otter trawl catches		
Woods Hole area 1943	79	64
Woods Hole area 1944	77	94
Off Stonington, Conn. 1943	146	163
Totals	562	601

Though the small numbers of *P. evolans strigatus* taken by trawl has resulted in limiting available sex ratio data to pound net sampling, it seems safe to infer that the 109 ♂♂ to 134 ♀♀ of this species taken in pound nets in the Woods Hole area in 1943 is also indicative of a ratio close to 1 to 1.

the abundance of the faster growing *P. evolans strigatus* (see section on age and rate of growth).

The otter trawl can operate quite independently of depth and proximity to shore. To be sure, it can only be used on relatively smooth bottom but there is little reason to expect this might effect the catches of these two species of *Prionotus,* both of which are fish of sand and mud bottoms. Certainly this limitation does not explain the above mentioned differences between pound net and trawl catches in Menemsha Bight where the latter gear was operated in the immediate vicinity of the pound net.

Being towed from a boat, the trawl operates without depending on the movements of the fish caught but escape from this gear may to some extent vary with the degree of activity of the species. The escape factor is probably small when a net with a good overhang is handled properly and of little consequence in modifying the relative catches of two species like these sea robins which are known from food habit studies (see section on food habits) and aquarium observations [5] to have the same bottom tending habits and apparently the same reaction to the chain line of a trawl. The mesh of a commercial otter trawl such as used on the New England coastal area is about 4 inches (stretched measure) and thus the faster growing *P. evolans strigatus* might be more subject to catch. The shrimp trawl with its fine mesh (1½ inches stretched measure) proved very effective in catching fish of small size as well as larger ones and, accordingly, was adopted for research purposes.

Considering these points which relate to mode of operation, my interpretation is that pound net catches do not constitute a good index of relative abundance. The more even ratios of *P. carolinus* to *P. evolans strigatus* in pound nets as contrasted with the trawl catches, show a greater tendency for the latter species either to frequent or to move about in shallow water within a couple of hundred yards of the shoreline; perhaps its tendencies are greater in both respects.

On the other hand trawler catches, if extensive enough, if applied to species living in comparatively rockless areas where a trawl can operate effectively, and if applied to species with similar bottom tending habits, offer a better index of relative abundance. Thus it is practical to summarize the available trawler catch records of *Prionotus* as a key to relative numbers. The catch from Fire Island was adequately sampled as previously mentioned and ten hauls made with a shrimp trawl on two trips to Menemsha Bight in 1944 were completely counted. The data are greatly limited but the approximate 50 *P. carolinus* to 1 *P. evolans strigatus* ratio that is obtained is in general accord with the many less perfectly sampled trawler records available as well as with the accounts given by experienced fishermen. The value of this ratio lies in the fact that it offsets the less accurate impression received from pound net catches and, crude as it is, it is better than vague descriptive terms.

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[5] A miniature imitation trawl chain line was hauled across the bottom of an aquarium containing small specimens (averaging about 5.0 cm. standard length) of both species. No difference in their reaction to the line was detected. Further aquarium observations on the small, also on larger specimens, failed to reveal species behavior differences but demonstrated the following features common to *P. carolinus* and *P. evolans strigatus:*

When extended, the large pectoral fins, often referred to as "wings," tend to volplane their bodies slowly downward through the water as described by Breder (1926).

The pectorals tend to hold the fish tight to the bottom as currents passing backward along the body strike the oblique fin surfaces. The currents resulting from opercular action tend to produce the same effect and thus there is little or no necessity for fin motion to counteract the forward thrusts from these currents.

The pectoral fins, held close to the sides of the body when the fish is progressing through the water at a relatively fast pace, effectively brake the forward motion when extended.

The large pectoral fins are not used in vaulting through the air. The above notes show that they are adapted to functions of a distinctly different sort.

The small sea robins observed had a jumping ability sufficient to clear the 4 cm. leap over the aquarium edge. The smallest measured *P. carolinus* known to leap over this barrier was 5.5 cm. standard length, the smallest measured *P. evolans strigatus* was 3.4 cm. standard length.

The three pairs of pectoral feelers (modified anterior rays of the pectoral fin), shown by Morrill (1895) to be richly supplied with touch receptors and to be used in searching for food, play no active part in locomotion.

Spawning

In an effort to establish the time of spawning, constant attention has been directed to the ovarian condition of the sea robins collected. With respect to *Prionotus carolinus* it can be said that ripe eggs, either in fresh condition or of the proper size in preserved ovaries (see description of eggs below), have been recorded from specimens taken from June 24 through August 9 in 1943, and from July 7 through July 28 in the lesser collections of 1944. At earlier and later dates the eggs were smaller, the largest eggs from specimens collected May 11 and September 12, 1943, being by actual measurement, half the size of mature eggs. To this we may add the opinion of Kuntz and Radcliffe (1918) who state: "This species spawns in June, July and early August. Fish ripe for stripping were taken in small numbers during the first half of July. Eggs were abundant in the plankton throughout July and were taken in small numbers as late as August 24." C. M. Breder, Jr., has generously permitted me to refer to certain unpublished notes dealing with studies he made in Atlantic City, New Jersey, in 1920. In these it is recorded that the first ripe *P. carolinus* were taken on August 19, a late date which he recognizes with the suggestion that it may be related to "the backward season." Perlmutter (1939) found eggs he identified as *P. carolinus* from May 12 through August 8 along the shores of Long Island and states that this species spawns from May through August in water from 55° F. to 76° F. In summary the above information establishes mid-June through early August as the spawning period in southern New England and vicinity and suggests an even longer period with possible variations as the seasons vary.

Ripe eggs, either in fresh condition or of the proper size in preserved specimens (see description of eggs below), have been recorded from ovaries of *P. evolans strigatus* taken as early as July 9 and as late as July 28, 1943. The only ripe fish noted in the lesser 1944 collections was one taken in Menemsha Bight, July 28. Measurement records show several fish with nearly ripe eggs taken during the last two weeks of June both years and, since records relating to degree of maturity (as judged by size) show many similarities between this species and *P. carolinus*, it may be that the discrepancy between the data for late June is the result of inadequate sampling. Summarizing its breeding season from the above data it may be said that *P. evolans strigatus* breeds through the month of July and perhaps in late June and early August, with possible changes as the seasons vary.

The measurement records show, also, that *P. carolinus* of about 14 cm. standard length and *P. evolans strigatus* of about 18 cm. standard length (both one-year-olds according to section on age and rate of growth) may produce ripe eggs. As would be expected of these small fish, the ovaries are small and the eggs comparatively few in number.

The appearance of the ovaries, which are similar in these two species, contributes to an understanding of their spawning. Variability of egg size and development is conspicuous throughout. The largest eggs, whether ripe or partially so, are not grouped but are scattered amongst less developed eggs of diverse sizes. Correlated with this is the fact that few eggs are ripe at any one time and the breeding season is somewhat prolonged.

Another feature is the diversity of ovarian condition noted when comparing individuals at any given date. For example, ovaries that were selected for their ripe appearance from a group of *P. carolinus* collected within a five-day period have shown, when compared in terms of the diameter of their largest eggs, a range from 0.2 mm. to 1.0 mm. This same tendency can be illustrated by the fact that of 70 adult female *P. carolinus* examined July 28, 1944, only 1 had ripe eggs, also of 7 adult female *P. evolans strigatus* measured on that date 2 had ripe eggs.

From the above information it appears that the inshore, shallow-water, summer distribution represents the spawning distribution of these two species. A similar correlation between inshore seasonal abundance and time of spawning of the grey gurnard, *Trigla gurnardus*, of the European coast, has been discussed in papers by Fulton (1899), McIntosh (1900), Meek (1915), and Hertling (1924), but collectively they did not establish an inshore spawning habit, for McIntosh (1900) proved the abundance of spawners offshore (about 25 miles) and in deep water (about 32 fathoms), and Meek (1915) discussed the adult grey gurnards as lingering somewhat offshore and in deeper water for spawning, later joining the immatures in shallow water. As yet there is no evidence to suggest the possibility of such offshore spawning in the two species of *Prionotus* under consideration, whereas ripe specimens are well known in the abundant shallow water populations.

The eggs of *P. carolinus* have been described by Kuntz and Radcliffe (1918) as follows:

> The eggs are spherical in form and 1 to 1.15 mm. in diameter. They are slightly yellowish in color, but highly transparent. The yolk sphere contains a variable number (10 to25) of oil globules of unequal size scattered over the surface. . . . . . The egg membrane is thin and horny.

My measurements of ripe eggs agree with these but Breder's unpublished notes, mentioned earlier in this section, give 0.94 to 0.99 mm. as the diameter. Breder gives a somewhat different description saying that the oil globules are "in a somewhat annular band which would, taking the germinal disc as the 'north pole,' describe the 'tropic of capricorn.' The eggs floated with the 'north pole' uppermost, giving the impression that the oil globules were not more buoyant than the surrounding protoplasm."

Kuntz and Radcliffe (1918) describe the development of the *P. carolinus* egg and remark that it is typical of pelagic teleost eggs. Also, that incubation at about 72° F. occupies about 60 hours, the larvae being about 2.8 mm. in total length at hatching (figures of this development are presented on pp. 106–107 of their paper). Eggs observed by Breder hatched in 89 hours at 68° to 70° F.

Except for eggs tentatively identified by Perlmutter (1939) as *P. evolans strigatus,* all descriptions of the eggs of this species that I have found in the literature apparently refer back to the questionably mature ones observed by Breder and described in his unpublished Atlantic City notes. He has informed me through correspondence that the descriptions given by Nichols and Breder (1927) and by Breder (1929) are from this source. In the latter paper the eggs are described as heavy, non-adhesive, transparent and averaging about 1.1 mm. in diameter. The transparency and diameter is supported by my records of the most developed eggs found in ovaries I have examined. The other two characteristics, particularly the demersal character, which is in sharp contrast to the properties of *P. carolinus* eggs, are open to question for these eggs were not successfully fertilized and buoyancy may be too delicately balanced to be determined from unfertilized eggs, even if they were known to be ripe. Doubt on this point was increased in my mind on observing that seemingly ripe but unfertilized *P. carolinus* eggs remained afloat for only a few minutes when placed in sea water; furthermore, such papers as that of Walford (1938) dealing with the delicate balance between the buoyancy of haddock eggs and sea water of varying density impress one with the complexities of this feature of a species' eggs.

AGE AND RATE OF GROWTH

Prionotus carolinus

The growth rate of *Prionotus carolinus* may first be analyzed on the basis of length-frequency distributions of populations sampled. Figure 1 (see p. 121) based on all fish taken by shrimp trawl in Menemsha Bight, Vineyard Sound, in 1943, lends itself to simple interpretation. It shows a mode at 4 cm. standard length,[6] another at 14 cm., and a third at 23 cm. The fish represented by the mode at 4 cm. were all collected on one trip, that of August 18. They are similar in size to other small *P. carolinus* taken in various habitats on dates immediately following the breeding season. All records of such small specimens are grouped together in the first mode of Figure 3. In addition to the Menemsha Bight fish this mode (Fig. 3) includes those taken with ½-inch (stretched measure) seine along the sandy beaches at Great Harbor, Woods Hole, on August 13 and 25, 1943; also those taken with shrimp trawl in from 2 to 10 fathoms in Buzzards Bay near the Weepecket Islands, August 27, 1943, and in from 2 to 7 fathoms in Vineyard Sound near Waquoit, September 2, 1943. The fish of all these collections are but slightly advanced over the fish 3.0 cm. in total length described by Kuntz and Radcliffe (1918) in concluding their account of the embryology and late larval development of this species; so there is little doubt that fish of this size and, therefore, the first mode of Figure 1, represent the young-of-the-year.

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[6] Standard length, used consistently throughout this paper except where otherwise noted, represents the distance from the tip of the snout to the posterior end of the vertebral column. The original measurements were made to the nearest ½ cm. and many were made directly in standard length by feeling the caudal vertebrae through the flesh, a technique checked by occasional dissections. Measurements made in total length, not preferred because of the frequency of damaged caudal fins, were changed to standard length by conversion as follows:

P. carolinus—standard length = 76.5% of total length
P. evolans strigatus—standard length = 78.4% of total length

It follows that the next mode of Figure 1 at about 14 cm., represents the one-year-olds and the third mode represents fish at least two years old.

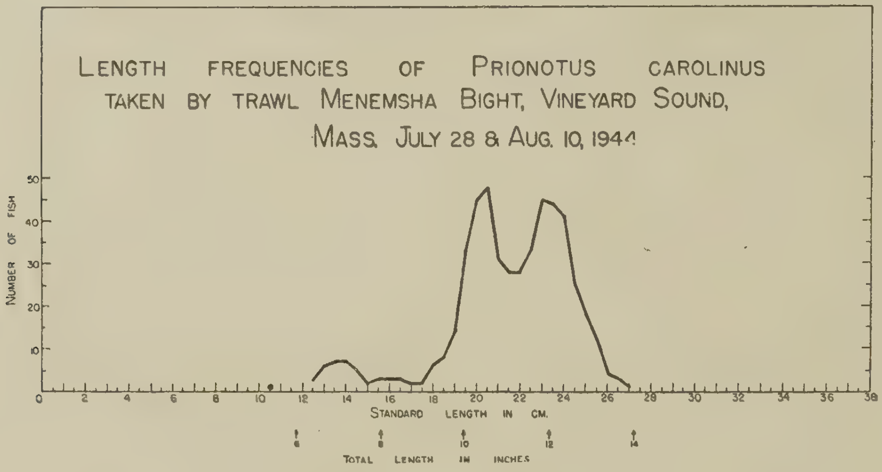

Fig. 2. Length–frequency distribution of *Prionotus carolinus* taken by shrimp trawl in less than 12 fathoms in Menemsha Bight, July 28 and August 10, 1944. Data smoothed as in Fig. 1.

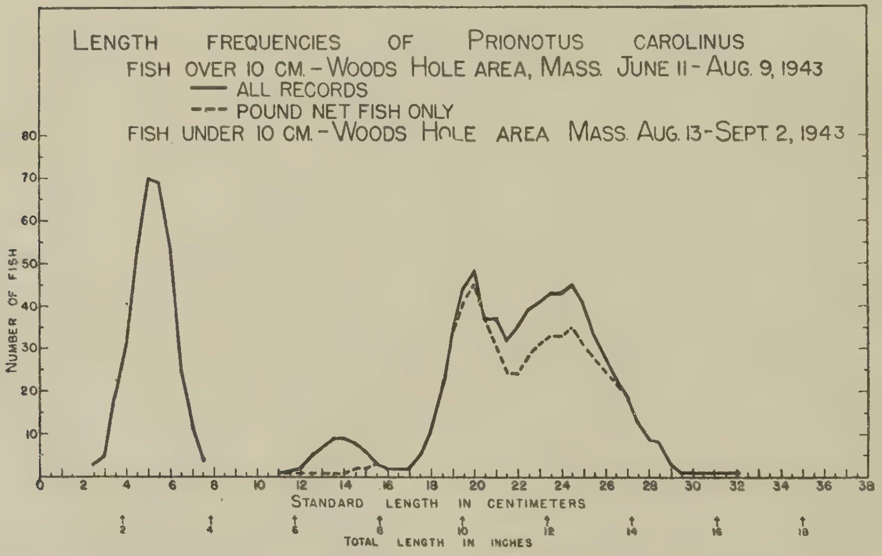

Fig. 3. Length–frequency distribution of *Prionotus carolinus* from the Woods Hole, Mass., area in 1943. All specimens over 10 cm. were taken from June 11 through August 9, with pound net catches shown by broken line and pound net plus shrimp trawl catches shown by solid line. The specimens under 10 cm. were taken from August 13 through September 2. Data smoothed as in Fig. 1.

Selectivity of gear is questionable as an explanation for the relatively large numbers in this 23 cm. mode as contrasted with the group at 14 cm. If there is any selectivity it must involve a tendency for the 14 cm. group to be distributed elsewhere, for this graph shows that the gear is quite capable of catching even the smallest size group. It is more probable that the relatively large size of the broad mode at 23 cm. is due, in part at least, to the summation of several age-groups two years old and above falling close together in the expected plateau phase of their growth curve.

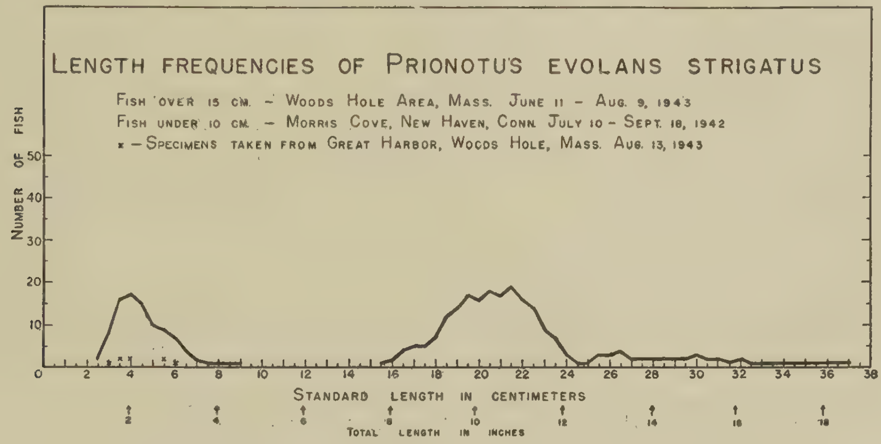

Fig. 4. Length–frequency distribution of *Prionotus evolans strigatus*. Includes specimens recorded from pound nets in the Woods Hole, Mass., area June 11 through August 9, 1943, and those taken by seine from Morris Cove, New Haven, Conn., July 10 through September 18, 1942, the former all being over 15 cm., the latter all being less than 10 cm. Data smoothed as in Fig. 1. Records of the small specimens collected from Great Harbor, Woods Hole, August 13, 1943, are inserted with cross marks.

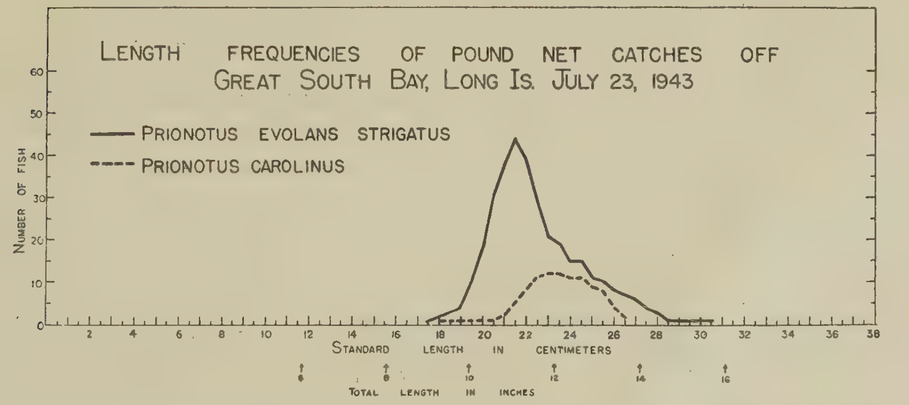

Fig. 5. Length–frequency distribution of *Prionotus carolinus* and *Prionotus evolans strigatus* which were sold on the wholesale market after being caught by pound net off Great South Bay, Long Island, July 23, 1943. Fish too small for marketing have been culled from these lots. Data smoothed as in Fig. 1.

Figure 2 represents shrimp trawl catches made in Menemsha Bight on two trips taken in 1944. No young-of-the-year were taken (the last of these trips being earlier than the August 18 date on which such specimens were collected in 1943) and few one-year-olds were taken, but, as far as available, the data do agree with those presented in Figure 1.

Figure 3 is a summary of all the *P. carolinus* measured from the Woods Hole region (Buzzards Bay and Vineyard Sound) during a selected 60-day period, June 11 through August 9, 1943, plus fish under 10 cm. standard length taken from August 13 through September 2, none of these having been collected during the earlier period selected for available records of larger specimens. If, in referring to this graph, one considers pound net catches only, there is no evidence of a mode at 14 cm. but this may well be the result of the large mesh of the gear and its questionable effectiveness in capturing smaller specimens. When the shrimp trawl catches are included, however, the mode becomes apparent in spite of the comparatively few trawler-caught fish involved. This graph, therefore, gives further support to the growth rate interpretation given to Figure 1.

In the third major mode of Figures 2 and 3 there is a suggestion of two smaller modes, one at about 20 cm. standard length and the other at about 23½ cm. This might be viewed as evidence of a two-year-old group averaging approximately 20 cm. in length and a group of fish three years and older averaging 23½ cm. Such a concept is not supported by Figure 1 or by the commercial trawl and pound net catches represented by Figures 5, 6, and 7. The numbers of fish in these two minor modes also have a bearing on the interpretation to be made. Figure 2, derived from shrimp trawl records considered comparatively free of selectivity, would contradict the expected tendency for numbers to decrease with age if either of these minor modes, both of which are larger than the 14 cm. mode, were represented as a distinct age-group. The possibility of dominant year-classes might be offered as an explanation of these relatively large numbers except that on such an assumption the large 20 cm. group should have been evident as a large 14 cm. mode (one-year-olds) in the previous year's records as given in Figure 1, possibly even in Figure 3. Also, if each minor mode noted, two in 1943 and two in 1944, were to be interpreted as a distinct year-class, the hypothesis would call for an improbable situation with three successive dominant year-classes.

Additional evidence as to growth rate may be obtained from scale studies. As Walford and Mosher (1943) so aptly state:

> The scales and otoliths of most fishes are characterized by folds or sculpturing in which variations of pattern may be related to age. If they are so related, for a given species, they need not correspond in number with years of life; or, if they do correspond, they may not be recognized, for they may be so obscure as to be counted incorrectly. It is no wonder, then, that scale and otolith reading is a process peculiarly open to subjective influences, and requires, for serious work, a stringent test and proof of validity.

In *P. carolinus* both scales and otoliths were examined. The latter were read in their entirety and along cut surfaces or sections, some of which were polished in an effort to bring out distinctive features; however, the extreme discrepancy in otolith readings from fish of the same length coupled with the easily observed variability in the type of otolith markings in material from different fish showed that these could not be used.

Early studies on the scales revealed markings so numerous, confused, and indistinct that no progress was made until a series of scales from one-year-old fish (as judged from the above interpretation of length-frequency data) was analyzed for the presence of a distinctive marking that might consistently appear on them.[7] With this series it was noted that by following the circuli from the focus outward one can detect a band, quite variable in width but usually running completely around that part of the scale in which circuli are present, where the circuli have not been laid down with their usual regularity (see Plate I). Continuing outward the regularity is again noticeable, with circuli often running in a somewhat different direction (not

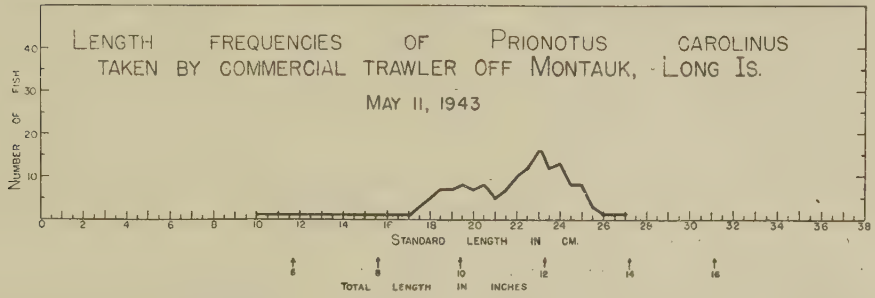

Fig. 6. Length–frequency distribution of *Prionotus carolinus* taken by commercial trawler off Montauk, Long Island, in about 8 fathoms, May 11, 1943. Data smoothed as in Fig. 1.

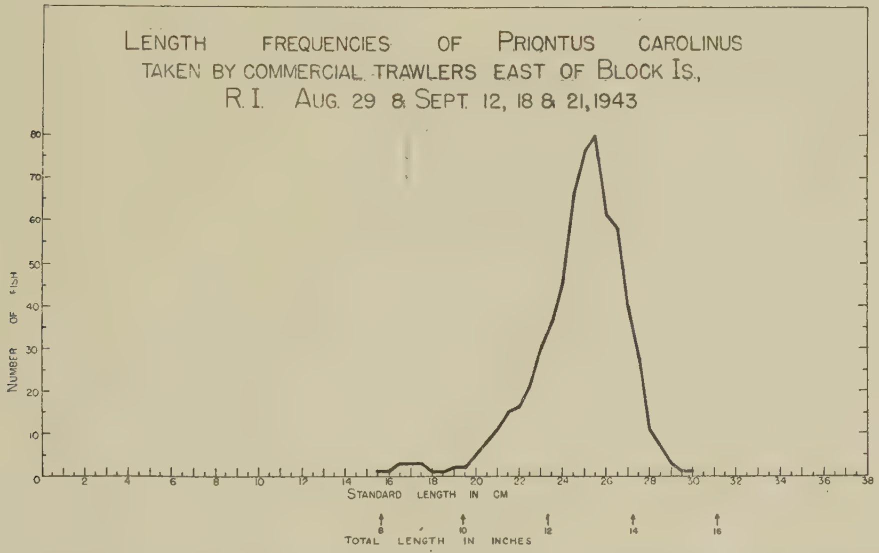

Fig. 7. Length-frequency distribution of *Prionotus carolinus* taken by commercial trawler east of Block Island, Rhode Island, in about 20 fathoms, August 29 and September 12, 18, and 21, 1943. Data smoothed as in Fig. 1.

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[7] Glycerin jelly mounts as recommended by Van Oosten (1929) proved useful for this study.

concentric with the inner ones) and often spaced differently than before. One such band was found on almost every scale of this series from one-year-old fish not only when they were read as a group but also when they were mixed with scales of fish of greater length and probably greater age and were read without knowledge of their identity. No band of this type was seen on scales from ten fish of the young-of-the-year length-group whereas an additional band of irregular circuli was usually found on scales from fish of about 20 cm. which, on the basis of length-frequency data, should be at least two years old. Thus this marking meets the specification of an annulus formed sometime before the summer collecting dates involved in this study. In practice it was found that the annulus could be most easily detected along the dorsal and ventral aspects of the scales and that the paths of regularly spaced circuli following the bands of irregularity were a great aid in locating these annual marks. It was also found that, in spite of the distinctiveness of the first annulus, the later markings were increasingly vague so any attempt to read scales that might have more than two annuli is fraught with error, a fact taken into account in the discussion of further scale studies which follows.

TABLE I

SUMMARY OF THE NUMBER OF *Prionotus carolinus* OF STATED LENGTH WITH SCALES READ AS HAVING 0, 1, 2, 3, OR 4 ANNULI

Standard length cm.	Number of annuli 0	I	II	III	IV	% of readings discarded, from the series indicated, because of illegibility and conflicting interpretation
Under 10	10					0%
12½–17½		28	1			6%
19		1				19%
19½		1	2			
20			7			
20½		1	6			
21			6	1		
22			1			
23			5	4		30%
23½				2		
24			1	4		
24½				3		
26			1			33%
27½						
28½					1	

The study of scales was continued by preparing mounts representing fish of various sizes, admittedly emphasizing such critical length-groups as those centering around 14, 20 and 23½ cm. All the scale slides were mixed and were read without reference to the length or even the species (scales from *P. evolans strigatus* were studied at the same time) until an interpretation had been made and recorded. Experience with micro-projectors, scale reading machines, binocular microscopes and dissecting microscopes showed the dissecting scopes to be most useful because of the field of vision, sharp image and desirable light control; consequently, at least two readings were made of every scale (except the simple ones from fish under 10 cm.) with such apparatus, the last two for each being listed under annuli number in the following table or included among those discarded if they did not concur.

Table I includes the observations already mentioned, to the effect that fish of the second mode, around 14 cm. on the length-frequency graphs, have one annulus. Thus two interdependent types of evidence, length-frequency and scale readings, support the interpretation that these are one-year-old fish. It may be further noted that fish of the third mode at 23 cm. have two annuli or more and thus are considered at least two years old.

The question as to whether there is a distinct 20 cm. group of two-year-olds, mentioned earlier in connection with the minor modes of Figures 2 and 3 may now be reviewed in the light of scale evidence. Of 31 fish 19 through 21 cm. in length, representing the first minor code, 21 showed two annular markings. Thus two annuli are commonly but not consistently found on scales of this group and, with 19 per cent of the scales discarded because of illegibility or conflicting readings, an exacting interpretation of the records would not seem justified. The lack of consistent readings is still greater for the 27 fish 23 through 24½ cm., representing the second minor mode, with only 13 giving the predominant 3 annuli reading and 30 per cent being discarded. This summary, correlated with the above-mentioned difficulty of reading successive annuli, does not support an age analysis based on these minor modes.

Weight records have been taken with length records on 435 *P. carolinus*. The standard deviation from a curve fitted to the arithmetic means of these weights is 1.52 oz.[8] By applying the method of least squares to the logarithms of the original data the following relationship was found:

$$W = .0104\, L^{2.99}$$

with W = weight in oz. and L = standard length in in.

The length-weight relationship derived from this sample is thus shown to be close to a cube relationship and might be handled as such for simplified conversions.

The length-weight records show that the 14 cm. (just over 7 in. total length) or one-year-old fish weigh from 1½ to 2 oz., and by the third summer (two-year-olds), when *P. carolinus* attains a length of 19 cm. or more (about 10 in. total length), the weight is over 4 oz. The heaviest fish recorded weighed 1 lb. 11½ oz. and was 14½ in. in total length.

Prionotus evolans strigatus

In considering the age and rate of growth of *Prionotus evolans strigatus* it is immediately recognized that the available length-frequency data are very limited. Catches made with the shrimp trawl, of marked value in the age study of *P. carolinus,* yielded so few specimens of this species (see section on relative abundance) that true length-frequency curves could not conceivably be drawn from the records. This limits the study to length-frequencies derived from pound net catches which, as explained above, are selective for fish of the larger sizes.

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[8] The standard deviation from the formula which follows would be no greater than and in all probability less than this.

In Figure 4 the *P. evolans strigatus* over 10 cm. are all those taken by pound net in the Woods Hole area during a sixty-day period, June 11 through August 9, in other words the same period used in preparing the length-frequency curve of pound net catches of *P. carolinus* as presented by dotted line in Figure 3. In analyzing the latter figure it was noted that fish under 17 cm. were not taken by the pound net gear except in disproportionately small numbers, this being true to the extent that a smaller age-group was missed altogether. This raises the question whether there is a length-group between the smaller fish taken, by minnow seine and represented by the mode centered at about 4 cm. in Figure 4, and the larger fish whose mode is centered at about 21 cm. There is little doubt but that the smaller fish, which were collected in shallow waters along the beaches soon after the spawning season and which have immature characteristics much like those of the small *P. carolinus* previously described, are young-of-the-year as proposed by Warfel and Merriman (1944). Whether *P. evolans strigatus* about 18 or 20 cm. in length, as shown in Figure 4, are one-year-olds demands careful consideration.

The answer to this question was derived from the study of the scales which had markings (see Plate I) very much like the annuli of *P. carolinus,* except that the distinctiveness noted in the first and sometimes the second annual rings of the latter was lacking from these *P. evolans strigatus* scales. With the exception of the simple scales of fish under 10 cm., at least two binocular microscope readings were made, the last two for each scale being listed in the following table by annuli number or included among those discarded if the readings did not concur. By studying these concurrently with scales of *P. carolinus* it was possible to make these readings without advance knowledge of either the species or the length.

From Table II it is noted that the large majority of smaller fish in the 21 cm. mode have only one annulus. Thus it appears that there is no length group of smaller fish and that this species attains a length of 17 cm. and more by the second summer. With little doubt the 21 cm. mode also includes fish more than one year old but the annuli are too obscure and other readings are too inconsistent to enable a breakdown into age groups.

Weight records have been taken with length records on 218 *P. evolans strigatus*. The standard deviation from a curve fitted to the arithmetic means of these weights is 1.81 oz.[9] By applying the method of least squares to the logarithms of the original data the following relationship was found:

$$W = .00880\ L^{3.12}$$

with W = weight in oz. and L = total length in in.

The length-weight relationship derived from this sampling is thus shown to be slightly greater than a cube relationship, a feature common in other fish analyzed for this according to Hart (1932) and Hile (1936).

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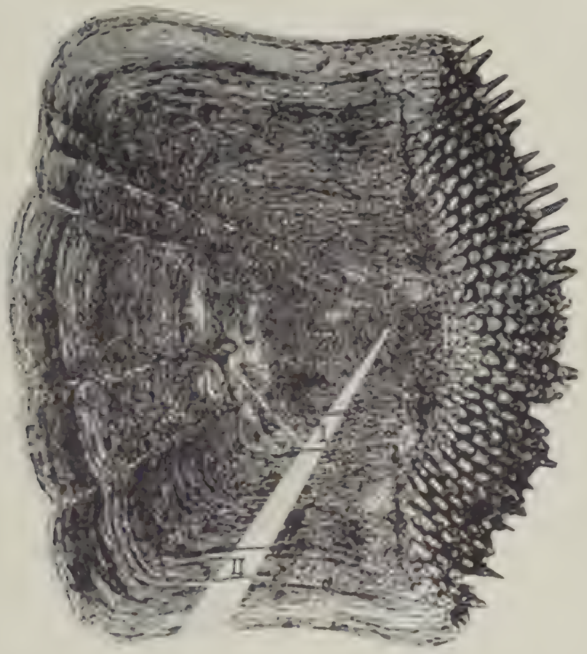
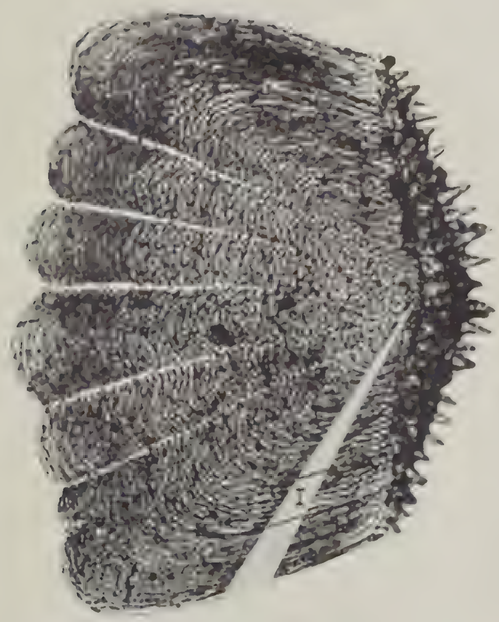
[9] The standard deviation from the formula which follows would be no greater than and in all probability less than this.





Upper. Scale from *Prionotus carolinus,* standard length 23 cm., collected August 18, 1943. First and second annuli are indicated by zones labeled "I" and "II" respectively. Actual dorso-ventral measurement of scale = 2.9 mm.

Lower. Scale from *Prionotus evolans strigatus,* standard length 20 cm., collected September 6, 1943. The one annulus present is indicated by zone labeled "I." Actual dorso-ventral measurement of scale = 3.0 mm.

The length-weight records show that by the second summer when the fish are 17 cm. or more (about 9 in. total length) this species has attained a weight of 4 oz. or more, comparing closely with the weight attained by *P. carolinus* in its third summer. This comparison and a comparison of the weight-length formulae show that, with the exception of the small young-of-the-year, *P. evolans strigatus* is decidedly the heavier of the two species at any given length. The implications of these comparisons in commercial practice are brought out in Figure 5 which shows, using the age-length relationships advanced in this paper, that one-year-old *P. evolans strigatus* were commonly saved as being sufficiently heavy for sale whereas the *P. carolinus* saved were at least two-year-olds, the majority probably older.

TABLE II

SUMMARY OF THE NUMBER OF *Prionotus evolans strigatus* OF STATED LENGTH WITH SCALES READ AS HAVING 0, 1, 2 OR 3 ANNULI

Standard length cm.	Number of annuli				% of readings discarded, from the series indicated, because of illegibility and conflicting interpretation
	0	I	II	III	
Under 10	10				0%
12½		1			
16					22%
16½		2			
17		3	1		
17½		3			
18		2			
18½		1			
19		5	1		
19½		1			27%
20		5			
20½		3	1		
21		4	2		
21½		1	3		
22		6	2	1	
22½		2	3		
23		2			
23½				1	
24			1		
25					44%
25½			2		
26			2	1	
26½			3		
27				1	
27½					
28				1	

The largest *P. evolans strigatus* recorded in this study had a total length of 18½ in. and a weight of 2 lbs. 9½ oz.

FOOD HABITS

The food habits of these two species were studied by analyzing the stomach contents of 216 *Prionotus carolinus* and of 62 *P. evolans strigatus*.

TABLE III

Stomach content analysis of 80 *P. carolinus* taken by trawl in the Woods Hole, Mass., area in 1943 comparing young-of-the-year (under 10 cm. standard length) with older fish

	42 fish (standard length 2.0—6.9 cm.)					38 fish (standard length 13—26 cm.)				
	No. eaten	% of total	No. of stomachs where found	Av. no. per stomach where found	Largest no. in one stomach	No. eaten	% of total	No. of stomachs where found	Av. no. per stomach where found	Largest no. in one stomach
Annelida, undetermined	4	<1%	2	2	2	18	1%	9	2	5
Copepoda, undetermined	549	55%	9	61	320					
Mysidacea	185	19%				2212	64%			
Mysis americana			8	23	40			14	158	1100
Michtheimysis stenolepis			1	1	1					
Cumacea	20	2%				1	<1%			
Diastylis sp.			4	2	2			1	1	1
Undetermined			6	2	3					
Amphipoda	156	16%				578	17%			
Tmetonyx sp.			1	6	6			1	3	3
Ampelisca sp.			4	2	4			9	8	50
Haustorius arenarius								1	1	1
Phoxocephalus holbölli								1	2	2
Gammarus locusta			2	1	1			20	24	124
Unciola irrorata			4	2	3			2	1	1
Gammaridea, undetermined			22	6	12			6	3	13

TABLE III (continued)

Isopoda, undetermined						1	<1%	1	1	1
Decapoda	67	7%				558	16%			
Crago septemspinosus			19	3	8			28	19	80
Natantia, undetermined			2	1	1			1	1	1
Upogebia affinis								1	2	2
Xanthidae, undetermined			3	1	2			3	6	15
Brachygnatha, undetermined			1	1	1			2	2	3
Megalops larva			4	1	2			1	1	1
Collembola, undetermined	1	<1%	1	1	1	1	<1%	1	1	1
Gastropoda	3	<1%				3	<1%			
Odostomia sp.			2	1	1					
Undetermined			1	1	1			3	1	2
Pelecypoda	1	<1%				54	2%			
Solemya velum								1	2	2
Tellina sp.								6	9	50
Undetermined			1	1	1					
Teleostomi	6	1%				4	<1%			
Prionotus carolinus								1	1	1
Heterosomata, undetermined			1	2	2					
Undetermined			4	1	2			3	1	1
Miscellaneous unidentified eggs			2	undetermined	undetermined					

Stomachs studied at first included 18 *P. carolinus* and 22 *P. evolans strigatus* captured in pound nets. The contents of these included many small crustacea plus a wide variety of fishes, including for example herring, *Clupea harengus,* whiting, *Merluccius bilinearis,* mackerel, *Scomber scombrus,* and cunner, *Tautogolabrus adspersus.* The size of the fish eaten was impressive, the outstanding example being the *P. evolans strigatus* 30½ cm. in standard length with a stomach containing four herring, each of which was about 15 cm. in total length. The condition of many of the fish eaten made it seem possible that they had been taken alive but, in view of the fact that these analyses were of *Prionotus* that had been confined in pound nets with other fishes, it seemed questionable that such piscivorous habits were natural. To answer this question and to get more accurate information on food habits, further study was limited to sea robins taken either by trawl or by seine, even though very few *P. evolans strigatus* could be obtained in this way. A quick glance at the various tables and other records of *Prionotus* stomach contents given below shows that these species are not piscivorous; moreover, it should be remarked that the few fish found in the stomachs were all of small size, probably young-of-the-year, and that full stomachs contained a total food volume far below that typically found in the fish-eating pound net specimens.

Tables III through VI present data from many of the stomachs analyzed arranged in groups to show comparisons.[10] Tables III and IV permit a comparison of *P. carolinus* taken from different coastal areas and during somewhat different seasons. They demonstrate that this species consistently feeds chiefly on a variety of small crustaceans such as can be found within a foot or so of the bottom.

Table III compares the food of *P. carolinus* hatched during the summer with that of the older fish and more records on the stomach contents of young-of-the-year of this species are included in Table V. The diets of these contrasting size groups are essentially the same except that the larger fish tend to consume the various food species in larger numbers. An impressive illustration from Table III shows that the young fish that ate *Mysis americana* had an average of 23 in their stomachs whereas the older, larger fish averaged 158. An outstanding exception is seen with respect to copepods,[11] which are eaten in large numbers by the young-of-the-year but are smaller than anything consumed by the older fish.

Available records are not sufficient for a similar tabulation of *P. evolans strigatus* stomach contents. Table VI lists stomach analyses of this species taken from Menemsha Bight in 1944 (none of this species was taken there in 1943) and compares them with analyses of *P. carolinus* of the same size and from the same area; i.e., taken with the same short haul of the shrimp trawl. Table V compares the young-of-the-year of both species as taken

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[10] A valuable service in the identification of certain puzzling amphipods was rendered by Clarence R. Shoemaker of the U.S. National Museum. Professor George L. Clarke, Mr. George M. Gray, Dr. Richard E. Lee, Professor J. S. Rankin, and many other Woods Hole investigators gave assistance in striving for accurate identification of stomach contents. Outstanding references used for this study included "Amphipoda of Southern New England" by Holmes (1905), "The Arthrostraca of Connecticut" by Kunkel (1918), and Verill and Smith's (1874) report on the invertebrates of Vineyard Sound.

[11] Professor George L. Clarke has identified some of these copepods for me and has determined the presence of several common species that frequent the shallow waters close to shore, including *Centropages hamatus* and *Pseudocalanus minutus.*

TABLE IV

	Stomach contents of 12 *P. carolinus* (standard length 18–24½ cm.) collected by trawl off Montauk, Long Island, May 11, 1943					Stomach contents of 13 *P. carolinus* (standard length 17–27½ cm.) collected by trawl east of Block Island, Rhode Island, September 18, 1943*				
	No. eaten	% of total	No. of stomachs where found	Av. no. per stomach where found	Largest no. in one stomach	No. eaten	% of total	No. of stomachs where found	Av. no. per stomach where found	Largest no. in one stomach
Annelida, undetermined						8	<1%	8	1	3
Mysidacea	20	16%				52	2%			
Mysis americana			5	4	10			4	13	28
Cumacea	22	17%				26	1%			
Diastylis sp.			2	1	1			5	4	7
Undetermined			4	5	11			3	2	4
Amphipoda	74	58%				2138	96%			
Archomenella pinguis								2	1	1
Ampelisca sp.								13	3	10
Phoxocephalus holbölli								3	1	1
Paraphoxus spinosus			1	1	1					
Monoculodes edwardsii			6	9	30					
Gammarus locusta								13	153	564
Cerapus tabularis								10	3	10
Unciola irrorata			1	1	1			11	4	15
Aeginella longicornis								6	5	8
Gammaridea, undetermined			3	6	30			1	1	1
Isopoda	3	2%								
Chiridotea caeca			3	1	1					
Decapoda	8	6%				2	<1%			
Crago septemspinosus			4	2	3			2	1	1
Pelecypoda						2	<1%			
Nucula sp.								1	1	1
Cardium pinnulatum								1	1	1
Teleostomi	1	1%								
Anguilla rostrata			1	1	1					
Miscellaneous unidentified eggs			3	undetermined	undetermined			4	undetermined	undetermined

* The stomach of one of these 13 fish was empty.

63 additional *P. carolinus* stomachs from fish collected off Block Island, September, 1943, were analyzed in the aggregate (without records for each individual) and were found to substantiate the above data.

TABLE V

Comparison of the stomach contents of young-of-the-year of *P. carolinus* and *P. evolans strigatus* taken by seine in Great Harbor 8/13/43

	P. evolans strigatus 10 fish (standard length 3.3—6.0 cm.)					*P. carolinus* 7 fish (standard length 4.1—5.6 cm.)				
	No. eaten	% of total	No. of stomachs where found	Av. no. per stomach where found	Largest no. in one stomach	No. eaten	% of total	No. of stomachs where found	Av. no. per stomach where found	Largest no. in one stomach
Annelida, undetermined						1	<1%	1	1	1
Copepoda, undetermined	912	98%	4	228	320	200	89%	2	100	160
Cumacea *Diastylis* sp.	1	<1%	1	1	1					
Amphipoda *Cerapus tabularis*						3	1%	1	3	3
Decapoda *Crago septemspinosus* Megalops larva	18	2%	9	2	4	19	8%	6 1	3 1	8 1
Teleostomi, undetermined						1	<1%	1	1	1
Miscellaneous unidentified eggs			4	undetermined	undetermined			3	undetermined	undetermined

TABLE VI

Stomach contents of 11 *P. evolans strigatus* taken from Menemsha Bight July 28 and August 10, 1944. From each haul in which this species was taken a corresponding number and similar size group of *P. carolinus* was analyzed for the comparison included in this table.

	Mysis americana			*Ampelisca* sp.			*Gammarus locusta*			*Crago septemspinosus*			*Tellina tenera*			*Prionotus carolinus*			Pleuronectidae, undetermined			Teleostomi, undetermined		
	No.	Av.	Max.	No.	Av.	Max.	No.	Av.	Max.	No.	Av.	Max.	No.	Av.	Max.	No.	Av.	Max.	No.	Av.	Max.	No.	Av.	Max.
Haul #1 July 28, 1941																								
4**P.e. strigatus* SL 21½–22½ cm.	2	69	112							4	5	10				1	1	1	2	4	4			
4 *P. carclinus* SL 20½–24 cm.	3	53	140	1	2	2	3	11	20	4	11	24	1	11	11							1	1	1
Haul #3 July 28,1944																								
2 *P.e. strigatus* SL 18½ & 22 cm.	1	1	1	1	3	3	1	128	128	1	8	8				1	5	5	1	1	1	2	1	1
2 *P. carolinus* SL 19 & 22 cm.	1	75	75				1	80	80	1	7	7	1	2	2							1	4	4
Haul #4 July 28, 1944																								
3 *P.e. strigatus* SL 21½–30 cm.	2	60	112	1	6	6	1	1	1	2	64	70				2	4	4				3	1	1
3**P. carolinus* SL 24½–26½ cm.	1	1	1	2	5	7	2	80	108				2	1	1									
Haul #1 August 10, 1944																								
1 *P.e. strigatus* SL 23 cm.	1	92	92							1	10	10										1	1	1
1 *P. carolinus* SL 23½ cm.	1	364	364	1	1	1				1	18	18												
Haul #2 August 10,1944																								
1 *P.e. strigatus* SL 20½ cm.										1	7	7				1	2	2				1	7	7
1 *P. carolinus* SL 18½ cm.				1	4	4	1	66	66	1	23	23	1	2	2									

* 1 of these fish had an empty stomach.

Key to columns: No. = no. of stomachs where found. Av. = average no. per stomach where found. Max. = largest no. in one stomach.

Other forms eaten in small numbers and mentioned here for completeness are:

for *P. carclinus*: Annelida, undetermined; *Michtheimysis stenolepis; Unicola irrorata;* Isopoda, undetermined; Natantia, undetermined; *Turbonilla elegans*

for *P. evolans strigatus*: Annelida, undetermined; *Michtheimysis stenolepis; Diastylis bispinosus; Unciola irrorata; Pagurus longicarpus; Cancer borealis;* Brachygnatha, undetermined; Megalops larva; *Ensis directus;* unidentified eggs.

together in Great Harbor, Woods Hole, August 13, 1943. The tables indicate a general similarity in the feeding habits of these two species, also demonstrated by the *P. evolans strigatus* caught in pound nets which contained, besides the fish mentioned earlier, a variety of small crustacea, etc., very similar to the variety found in *P. carolinus* stomachs and undoubtedly consumed before the fish entered the pound.

Twenty-eight young-of-the-year *P. evolans strigatus* collected in Morris Cove, New Haven, Connecticut, on August 7 and 21 and September 4, 1942, had eaten only *Crago septemspinosus* (except for one fish that had also consumed three undetermined teleosts). The latter feeding is far more uniform than observed elsewhere in my analyses for either species. It would seem to indicate a high availability of the *Crago* eaten and the probability is that, under similar conditions, *P. carolinus* would have eaten the same.

From Table VI it may be noted that, though fish remained a very minor article of the diet, the *P. evolans strigatus* analyzed had eaten more of them than had *P. carolinus*. Data on this possible difference is meagre but this table points to what may be a definite tendency. In the collections made from Vineyard Sound, near Waquoit, September 2, 1943, of four *P. carolinus* analyzed (about 17 cm. standard length) one had a young *P. carolinus* in its stomach and all had eaten the typical assortment of small crustacea; whereas, of the two *P. evolans strigatus* taken, one (23½ cm. standard length) had eaten a small flying squirrel, *Cephalacanthus volitans,* the other (12½ cm. standard length) had eaten an unidentified teleost and neither fish showed any other food of consequence in its stomach. And from the "Hell Hole" northeast of Block Island, Rhode Island, fifty-two large *P. carolinus* had fed largely on a variety of small crustacea, whereas the one large *P. evolans strigatus* taken on the same date had eaten forty-five of the small shrimp, *Palaemonetes vulgaris* and one skate, *Raja erinacea.* Certainly its larger mouth and its rapid rate of growth would correlate with the interpretation that *P. evolans strigatus* is the more piscivorous of these two species.

There are certain factors not evident from tabular form that should be mentioned. The annelida found were in distorted form, not lending themselves to identification. Perhaps mechanical and digestive effects account for the poor condition of these soft-bodied forms as contrasted with the more typical food organisms having resistant exoskeletons, etc. Not indicated in the tables is the fact that a large majority of the stomachs examined contained a few sand grains and hard inorganic particles of sand grain dimensions. A few stomachs contained small scraps of plant tissues ranging from fragments of larger plant detritus to bits of the smaller filamentous algae.

The data given are in general agreement with scattered published reports (often in the form of brief comments on a few fish examined) on the food habits of these species, such notes being found for example in Sumner, Cole and Osburn (1913), Bigelow and Welsh (1925), and Hildebrand and Schroeder (1938). Summarizing the present, more complete study, it can be said that small crustacea were eaten by *P. carolinus* and *P. evolans strigatus* in far greater numbers and in greater amounts by volume and weight than were the members of any other class or phylum. Narrowing comparisons to orders it is evident that the Amphipoda were represented in greatest variety, weight and volume. The amphipod, *Gammarus locusta,* and the mysid, *Mysis americana,* were the two most abundant species in the stomachs analyzed, the former being decidedly the more important in terms of weight. The smallest forms eaten were the copepods which, as mentioned above, were frequently found in large numbers in the stomachs of the young-of-the-year. *Crago septemspinosus* represents the maximum size of the food species commonly found and, while its numbers were seldom great, the comparatively large volume of individual specimens ranks it as an outstanding item.

Though they have diverse habits (some are burrowers and some are commonly found at mid-depths as plankton), practically all these food species frequent the zone on and within a foot or two above the bottom deposits. The use of this zone on and over the bottom is emphasized by a comparison of the stomach contents of *Prionotus* taken in Menemsha Bight and the relative abundance of bottom invertebrates in the Bight as reported by Lee (1944) from a quantitative study of bottom samples. *Mysis americana, Gammarus locusta,* and *Crago septemspinosus* were the most numerous forms in the *Prionotus* stomachs but none of these are in the list of the eight most common organisms taken in Lee's samples. In fact *Mysis americana* is not mentioned in the published record of these samples and, like several other forms in the *Prionotus* diet, was probably taken in very small numbers if at all, for his bottom sampler would bring up a given portion of sand and mud useful for a quantitative measure of organisms burrowing therein but not suitable for observations on the fauna immediately over the bottom. Some correlation might be expected between the abundance of organisms in such bottom samples and the stomach contents of species eating from the actual bottom deposits. On the other hand, should the fish involved eat predominantly from the fauna just above, or on but not burrowed in the bottom materials, such a correlation would be lacking as in *P. carolinus* and *P. evolans strigatus.*

A bottom of fine sand was found by Lee (1944) to have the richest fauna of the five distinct bottom types he recognized in Menemsha Bight. The fact that the *Prionotus* were taken in greatest numbers over this type bottom may well indicate that this high productivity in the bottom sediments is matched by a comparable abundance of animals directly over them.

Summary

The life histories of the common sea robin, *Prionotus carolinus,* and the northern striped sea robin, *P. evolans strigatus,* were investigated simultaneously and thus on a comparative basis. In the southern New England coastal waters, where this study was undertaken, both species are abundant from late April, when the inshore temperature is just above 40° F., till late in October, when the temperature has dropped slightly below 60° F. Their presence inshore overlaps their respective spawning seasons, which extend from mid-June through early August for *P. carolinus* and for about the same period, possibly somewhat shorter, for *P. evolans strigatus.*

Records from commercial fish trawlers and shrimp trawls used for research are discussed as valid indicators of relative abundance of these two common species. Such data indicate a ratio of about 50 *P. carolinus* to 1

P. evolans strigatus in the region studied. Disproportionately high pound net catches of *P. evolans strigatus* are interpreted as resulting from a greater tendency for this species to inhabit or to move about in waters within a couple of hundred yards of the shore; perhaps both factors are involved.

Length-group and scale studies indicate that *P. carolinus* attains a standard length of about 14 cm. (just over 7 in. total length) and a weight of 1½ to 2 oz. during the second summer (as one-year-olds) and a length of 19 cm. or more (about 10 in. total length) with a weight of over 4 oz. during its third summer. Similar studies show that *P. evolans strigatus* attains a standard length of 17 cm. or more (about 9 in. total length) with a weight of 4 oz. or more in its second summer, being almost as large as specimens of *P. carolinus* a year older. In both species one-year-olds were found with eggs of mature size though the ovaries and egg numbers were small.

Detailed analyses of 278 stomachs of *P. carolinus* and *P. evolans strigatus* were made. The records show that both fish feed chiefly on small crustacea that occur on or within a few inches of the bottom in the sand and mud areas where these fish are found. In number of species, number of individuals and volume, the Amphipoda exceeded all other orders in the stomach contents. *Gammarus locusta, Mysis americana* and *Crago septemspinosus* were the outstanding species found in the fish examined. Very few fish were found in the stomachs studied. The only marked difference between the food habits of larger and smaller fish was a rough correlation between size of the fish and volume of its stomach contents, the larger fish having taken food species in roughly the same proportions but in greater numbers.

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Contribution No. 342

The design of a paint to approach this ideal depends upon the properties of the toxic ingredients as well as those of the binder or matrix. The present series of papers describes the relevant properties of certain commonly used and effective toxics and toxic-matrix systems.

The primary characteristic of the toxic is its solubility. The classical dilemma in the theory of toxic action, as stated by Young (*12*), is that an insoluble toxic will be ineffective and a soluble toxic will be washed away to leave an exhausted surface. The selection of a toxic with an adequate, but not excessive, solubility may facilitate the resolution of this dilemma. This paper and the one to follow (*3*) are concerned with the solubilities and rates of solution of toxics in sea water.

By far the most widely used toxic substance in ship-bottom paints is cuprous oxide. The solubility of this material in sea water can be measured only in the absence of oxygen, since cuprous copper is rapidly oxidized in solution. This paper reports a study of the solubility of cuprous oxide in air-free sea water, and the dependence of its rate of solution in sea water and other chloride solutions upon temperature, hydrogen and chloride ion concentrations, and ionic strength.

The solubility measurements were carried out with Baker's C.P. cuprous oxide. The rate measurements were made with an electrolytically prepared cuprous oxide, compounded with a small proportion of insoluble binder.

MEASUREMENT OF SOLUBILITY

Cuprous oxide was placed in the equilibration vessel, which was then evacuated and flushed with nitrogen. Air-free sea water was forced into the vessel under nitrogen pressure. In some cases agitation was produced by bubbling nitrogen; in others, the vessel was closed, disconnected, and rotated in a water bath. All equilibrations were made at 25° C. After equilibration, the solution was forced out through a sealed-in sintered glass filter by applying nitrogen pressure, and samples were collected for analysis. The pH was quickly measured with a Beckman glass electrode. After exposure to the air, the cuprous copper in solution became oxidized to the cupric form, and was partially reprecipitated as a mixture of basic cupric carbonate and oxychloride (*3*). Any such precipitate was redissolved by adding citric acid, and the copper content was determined colorimetrically with sodium diethyl dithiocarbamate (*2*, *5*).

Further details in procedure for several different series of solubility measurements follow:

SERIES 1. The sea water was deaerated by evacuation and flushing with nitrogen, and the pH was allowed to rise as carbon dioxide was removed along with oxygen.

SERIES 2. The sea water was treated to remove carbonates by addition of hydrochloric acid following the procedure of McClendon *et al.* (*8*), and the pH was adjusted by addition of sodium hydroxide. Subsequent deaeration did not change the pH.

SERIES 3. The sea water was deaerated as before, and a small amount of gaseous carbon dioxide was introduced to bring the pH back to approximately that of normal sea water.

SERIES 4. The procedure was the same as in series 3, except that the nitrogen was freed of the last traces of oxygen by passing it over hot copper turnings, and extreme precautions were taken in evacuating and flushing the equilibration vessel and its connections.

SERIES 5. The procedure was the same as in series 4, except that the saturating body, instead of being finely divided cuprous oxide, was a surface coated with a mixture of cuprous oxide, celite, rosin, and Vinylite resin.

TABLE I. SOLUBILITY OF CUPROUS OXIDE IN OXYGEN-FREE SEA WATER

pH	Solubility, Moles Cu/ Liter × 10^4	Series No.	pH	Solubility, Moles Cu/ Liter × 10^4	Series No.
7.11	8.35	5	8.51	0.26	4
7.40	3.26	2	8.56	0.29	4
7.70	2.34	2	8.60	0.22	1
7.80	1.73	3	8.73	0.14	1
8.12	0.74	3	8.88	0.11	1
8.12	1.57	1	8.92	0.19	1
8.46	0.49	4	8.96	0.14	1

The solubilities of cuprous oxide measured at 25° C. are given in Table I and their logarithms are plotted against pH in Figure 1. Concentrations are given in moles (gram atoms) of copper—i.e., half moles of cuprous oxide—per liter.

The data are well represented by the equation,

$$\log S = 4.03 - \mathrm{pH}$$

which shows that the solubility is directly proportional to the hydrogen ion concentration. The solubility of cuprous oxide in normal sea water, of pH 8.1, is 8.6×10^{-5} moles of copper per liter.

Bodländer and Storbeck (*1*) showed that cuprous ion in chloride solutions forms the complexes $CuCl_2^-$ and $CuCl_3^{--}$. It may be assumed that the following equilibria are established between cuprous oxide and sea water:

$$\begin{aligned} {}^1/_2Cu_2O + {}^1/_2H_2O &= Cu^+ + OH^- \\ Cu^+ + 2Cl^- &= CuCl_2^- \\ Cu^+ + 3Cl^- &= CuCl_3^{--} \end{aligned}$$

These equilibria are described by the equations

$$\begin{aligned} (Cu^+) &= k_s(H^+)/k_w \\ (CuCl_2^-) &= k_2(Cu^+)(Cl^-)^2 \\ (CuCl_3^{--}) &= k_3(Cu^+)(Cl^-)^3 \end{aligned}$$

where k_s = solubility product $(Cu^+)(OH^-)$
k_w = ion product $(H^+)(OH^-)$
k_2, k_3 = association constants for respective complexes

On this basis the expected solubility of cuprous oxide can be calculated from data in the literature. We take the values $k_s = 1.2 \times 10^{-15}$ and $k_w = 1.0 \times 10^{-14}$ from Latimer (*6*), and $k_3 = 6.9 \times 10^5$ from Náray-Szabó and Szabó (*9*). The constant k_2 is derived from the value of $(CuCl_2^-)/(Cl^-)$ in equilibrium with cuprous chloride, given by Noyes and Chow (*10*) as 0.066, and the solubility product of cuprous chloride (*6*), 1.85×10^{-7}; thus $k_2 = 3.5 \times 10^5$. In sea water chloride ion concentration[2] is 0.48 *M*:

---

[2] There is, of course, some variation in chloride content (*7*); the value of 0.48 *M* (17 parts per thousand) was selected as a standard for laboratory investigations of antifouling paints (*5*).

The total dissolved cuprous copper is the sum of the concentrations of $CuCl_2^-$ and $CuCl_3^{--}$, free cuprous ion being negligible by comparison. The solubility of cuprous oxide in sea water, expressed as moles of copper per liter, is calculated from these data to be

$$(9.7\gamma^2_{Cl^-}/\gamma_{CuCl_2^-} + 9.2\gamma^3_{Cl^-}/\gamma_{CuCl_3^{--}}) \times 10^3(H^+)$$

where γ = activity coefficient of ion indicated

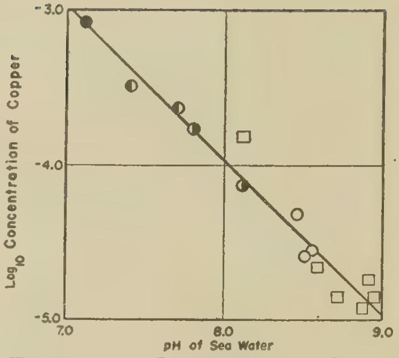

Figure 1. Logarithm of Solubility of Cuprous Oxide (in Moles of Copper per Liter) in Sea Water *vs.* pH

□ series 1, ◐ series 2, ◑ series 3, ○ series 4, ● series 5

This expression reduces to the experimentally determined function if all the activity coefficients are taken as 0.67, a reasonable value in sea water, the ionic strength of which (*7*) is 0.63. The agreement between calculated and measured solubilities indicates that the ionic equilibria of cuprous ion in sea water are the same as those which have been described for simpler systems containing chloride ions.

EFFECT OF OXYGEN ON RATE OF SOLUTION

Studies of the rate of solution of cuprous oxide were made on glass surfaces coated with cuprous oxide suspended in a binder. The exposed area of solute is not known under these circumstances, but the data provide relative measurements of the dependence of rate of solution upon different experimental conditions. The order of magnitude of the specific rate constant for solution can also be estimated from these studies.

In air the copper dissolved from cuprous oxide in sea water is oxidized and is eventually partially reprecipitated as a mixture of basic cupric carbonate and chloride. However, the rate of solution from a surface covered with cuprous oxide does not appear to be affected by the presence of oxygen.

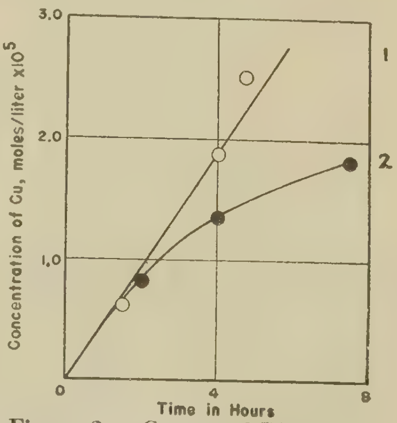

Figure 2. Course of Dissolution of Cuprous Oxide, (1) in the Absence of Air and (2) in the Presence of Air

Microscope slides (total area 39 sq. cm.) were coated with a standard Navy paint of the "cold plastic" type containing 40% of cuprous oxide, and were rigidly supported inside centrifuge bottles containing 190 cc. of sea water. The bottles were rotated at 30 r.p.m., and samples were withdrawn at different times for analysis. The analytical method was the same as in the solubility measurements. This experiment was performed both in the presence of air and with careful exclusion of air (as in series 4 of the solubility measurements). The results are given in Figure 2. Although the rate of solution in air falls off after a copper concentration of 1×10^{-5} *M* has been attained, the initial rates with and without atmospheric oxygen appear to be the same. The remaining experiments were carried out in the presence of air, using the following procedure.

Three different cuprous oxide coatings were applied with a volatile solvent to ground glass panels 3 × 4 inches in size. Their dry compositions were as follows: 1, 90% cuprous oxide, 10% Vinylite resin; 2, 80% cuprous oxide, 20% Vinylite; 3, 80% cuprous oxide, 15% Vinylite, and 5% rosin.

Each panel was agitated in 1500 cc. of sea water by an apparatus, originally designed for Warburg respirometers, which produced an oscillatory motion of the panel perpendicular to its own plane. Both the frequency of oscillation and the distance of travel could be varied. Samples of solution were removed at intervals for analysis. The rate of solution was calculated as moles of copper (half moles of cuprous oxide) per sq. cm. of panel surface per second. According to the time intervals chosen, agreement between successive values of the rate of solution showed that the course of dissolution followed the linear portion of the curve in Figure 2.

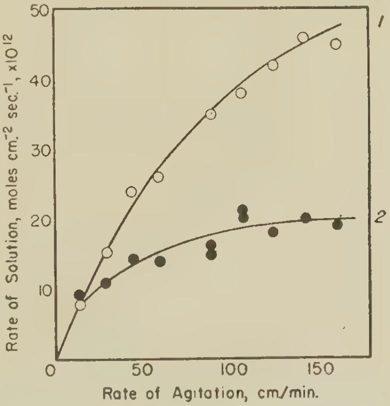

Figure 3. Rate of Solution of Cuprous Oxide in Sea Water Plotted against Rate of Agitation

Curve 1 = coating 1; curve 2 = coating 2

The agreement between values of the rate of solution determined over successive time intervals also showed that the area of exposed cuprous oxide was not varying during the experiment. Occasionally, however, the initial value was low and was discarded. It was concluded that, if the binder formed any superficial layer of resin on the cuprous oxide particles exposed at the surface of the coating, it must have been very tenuous and, ordinarily, quickly removed after immersion.

The rates of solution from three panels which had been coated at the same time were usually measured simultaneously under identical conditions; the agreement in the individual values was ordinarily within 15%. The average of the three values is reported in each case.

EFFECT OF AGITATION ON SOLUTION RATE

The rates of solution from three panels covered with coatings 1 and 2 were measured in normal sea water at 20° C. under different conditions of agitation. The frequency of oscillation was varied from 75 to 135 cycles per minute and the distance of travel from 0.2 to 1.2 cm. The product of frequency and distance was taken as a measure of the agitation, and the results are plotted against this quantity in Figure 3. In the case of coating 2, containing 80% of cuprous oxide, the rate of solution appears to have attained a maximum value at the highest agitation employed, and it may be concluded that processes of diffusion at the surface are not limiting the solution rate under these conditions. Coating 1, which contains 90% cuprous oxide, and therefore presumably carries a greater area of exposed solute per unit of panel surface, has not attained a maximum rate of solution under the most violent conditions of agitation employed.

By adjusting the conditions of agitation and the area of exposed solute, the effect of diffusion on the solution rate can be either eliminated or made predominant. Coating 1 provided a large area of exposed cuprous oxide, and coatings 2 and 3 smaller areas, per unit of panel surface. Subsequent measurements were made under three different conditions: (*a*) with coating 2 or 3, at high agitation, where the effect of diffusion is eliminated; (*b*) with coating 1, at high agitation, where the effect of diffusion is slight; (*c*) with coating 1, at low agitation, where the effect of diffusion predominates.

EFFECT OF TEMPERATURE ON SOLUTION RATE

The rates of solution of three panels covered with each of coatings 1 and 3 were measured in normal sea water at several different temperatures from 0° to 36.5° C. Several conditions of agitation were also employed; the rates of solution obtained at rates of agitation of 108, 126, 144, and 162 cm. per minute were averaged at each temperature. The results, given in Table II, show a range of about fourfold over the temperature range employed. In the neighborhood of 20° C. the change of the measured rate of solution with temperature is about 3% per ° C.

The measured rates of solution do not reflect the effect of temperature alone, since the pH of sea water in equilibrium with atmospheric carbon dioxide increases with increasing temperature. Table II also gives the pH shifts from a temperature of 0° C., taken from the data of McClendon (*8*); our own measurements of pH confirmed the magnitude of these shifts, showing that equilibrium with the atmosphere was established under our experimental conditions.

In order to calculate the effect of temperature alone on rate of solution, the measured values were corrected to the pH at 0° C. on the assumption that the rate is directly proportional to the hydrogen ion concentration, as shown in the next section. These values are also given in Table II, and their logarithms are plotted against the reciprocal absolute temperature in Figure 4. For coating 3, containing 80% of cuprous oxide, the Arrhenius relation appears to be quite closely followed; the slope of the straight line corresponds to an activation energy of 12,000 calories. The magnitude of this value is further indication that diffusion is not limiting the rate of solution under the conditions employed. For coating 1, containing 90% of cuprous oxide, the points fall on a line with the same slope at the lower temperatures. At the higher temperatures the points fall off somewhat, a further indication that diffusion influences the rate of solution to a slight extent when a larger area of cuprous oxide is exposed.

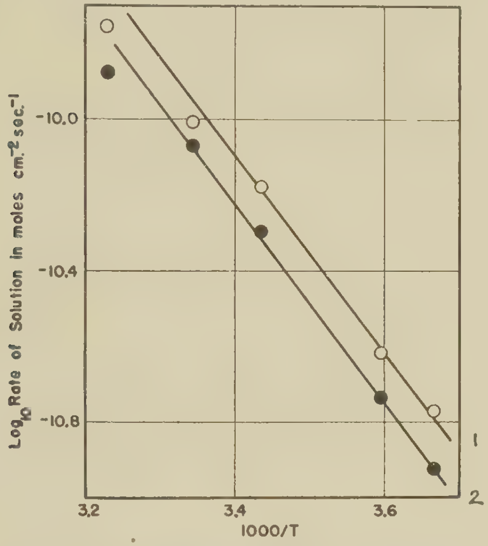

Figure 4. Rate of Solution of Cuprous Oxide in Sea Water, Plotted Logarithmically against Reciprocal Absolute Temperature after Correction for Shift in pH

Curve 1 = coating 1; curve 2 = coating 3

TABLE II. DEPENDENCE OF RATE OF SOLUTION OF CUPROUS OXIDE IN SEA WATER ON TEMPERATURE

		Rate of Soln., Moles Cu/Sq. Cm./Sec. × 10^{12}			
Temp., ° C.	pH Shift from 0° C.	Coating 1 measured	Coating 3 measured	Coating 1 corrected for pH	Coating 3 corrected for pH
0	0	17.1	12.0	17.1	12.0
5	0.085	19.8	15.3	24.2	18.6
18	0.225	39.8	30.0	66.8	50.4
26	0.300	50.0	42.7	100	85.4
36.5	0.400	70.2	52.6	177	132

Most subsequent measurements were made at 20° C., and those made at slightly different temperatures (between 20° and 25°) were reduced to 20° by applying a correction of 3% per ° C. (Table II).

EFFECT OF pH ON SOLUTION RATE

For study of the effect of hydrogen ion concentration, artificial solvents were employed, containing 0.48 *M* sodium chloride and 0.1 *M* borate buffer, with the pH ranging from 7.08 to 8.48.

In the course of measurements in artificial solvents, in this series and those described later, many different sets of triplicate panels were employed. Their rates of solution in normal sea water at an agitation of 144 cm. per minute were measured before and after the determinations in the artificial solvents. The rates at the beginning and at the end of the experiment agreed usually within 15% and often within 5%, an indication that no sensible change in the surface of the cuprous oxide had occurred during the measurements. Usually each set of panels was used successively in several different artificial solvents. The averages of the rates at beginning and end showed considerable variation, ranging from 37 to 65 $\times 10^{-12}$ mole cm.$^{-2}$ sec.$^{-1}$ with most of the values falling between 46 and 56. This variation was attributed to differences in the area of exposed cuprous oxide, due to uncontrolled conditions in the coating of panels and evaporation of solvent from the binder. Accordingly, all results were reduced to a standard sea water solution rate of 50 $\times 10^{-12}$ by multiplying by the factor $50/R_s$, where R_s is the average sea water solution rate for the particular set of panels employed.

TABLE III. EFFECT OF pH ON RATE OF SOLUTION OF CUPROUS OXIDE IN SODIUM CHLORIDE-BORATE BUFFERS AT 20° C. (COATING 1)

pH	Rate of Soln.[a], Moles Cm.$^{-2}$ Sec.$^{-1}$, $\times 10^{12}$ Agitation, 15 cm./min.	Rate of Soln.[a], Moles Cm.$^{-2}$ Sec.$^{-1}$, $\times 10^{12}$ Agitation, 162 cm./min.
7.08	95	430
7.29	67	250
7.48	49	178
7.65	34	133
7.83	18	60
7.89	..	67
7.89	..	63
8.18	11.6	42
8.48	6.4	32

[a] Reduced to a standard sea water solution rate of 50 $\times 10^{-12}$.

The results of varying the pH are given in Table III and the rates of solution are plotted logarithmically against pH in Figure 5. The points for high agitation, at which the influence of diffusion may be expected to be slight, lie along a straight line with a slope of −0.94. This is probably not significantly different from −1, and it may be concluded that the rate of solution of cuprous oxide in sodium chloride solutions is proportional to the hydrogen ion concentration. The points for low agitation lie along a line with a slope of −0.85. Even when the dissolution is controlled largely by diffusion, therefore, its rate is not very far from proportional to the hydrogen ion concentration.

The rates of solution in sea water, also plotted in Figure 5, are somewhat lower than in a buffer solution with the same pH and chloride concentration.

EFFECT OF CHLORIDE ION CONCENTRATION

The effect of chloride ion concentration on rate of solution was investigated in sodium chloride solutions containing 0.1 *M* borate buffer at pH 7.88. (Allowance was made for deviations of a few hundredths of a pH unit by correcting the results to 7.88, the prevailing pH of the laboratory sea water, with the rate of solution considered proportional to the hydrogen ion concentration.) The contribution of the borate to the ionic strength was taken as 0.03. At chloride concentrations below 0.48 *M*, the ionic strength was kept constant at 0.51 by replacing sodium chloride with sodium nitrate. Above 0.48 *M*, the ionic strength increased with the chloride concentration; however, as shown below, the effect of ionic strength on the rate of solution of cuprous oxide is small in this range, so that this series demonstrates essentially the effect of chloride concentration at constant ionic strength. The conditions of agitation were chosen both to minimize and to emphasize the effect of diffusion.

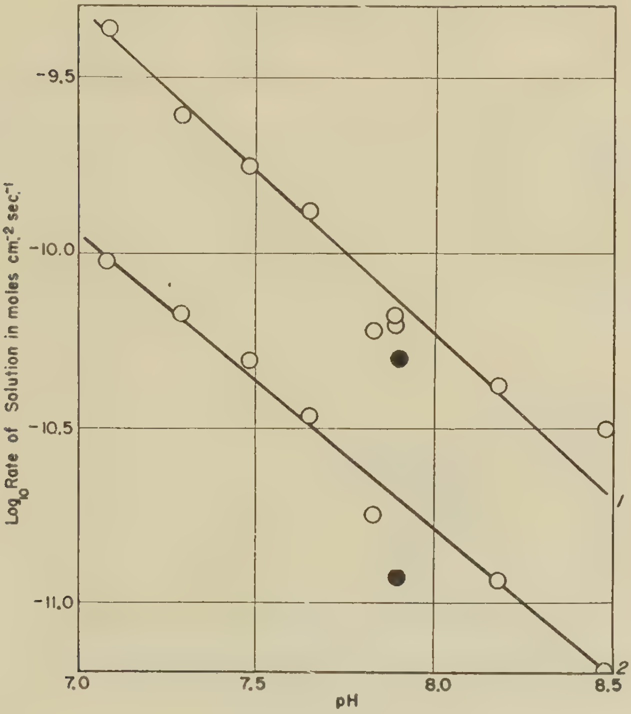

Figure 5. Rate of Solution of Cuprous Oxide from Coating 1 in Artificial Solvents ○, and in Sea Water ●, Plotted Logarithmically against pH

Curve 1, agitation = 162 cm./min.; curve 2, agitation = 15 cm./min.

The values for rate of solution for coating 1 were reduced to a standard sea water solution rate of 50×10^{-12} as described in the preceding section, and those for coating 2 were similarly reduced to a standard rate of 20 × 10^{-12}. The data are given in Table IV and plotted in Figure 6 against the square of the chloride ion concentration. It is apparent that the rate of solution is a linear function of the square of the chloride ion concentration, at both high and low agitation.

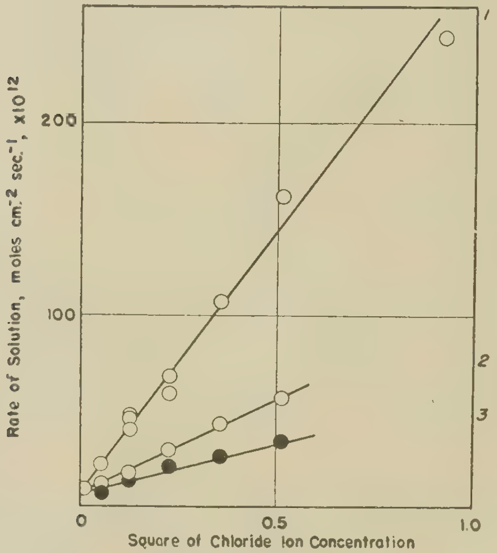

Figure 6. Rate of Solution of Cuprous Oxide in Artificial Solvents, Plotted against the Square of the Chloride Concentration

1, coating 1, agitation 144 cm./min.; 2, coating 1, agitation 15 cm./min.; 3, coating 2, agitation 144 cm./min.

The intercept at zero chloride concentration, which for coating 1 at high agitation is about 7 × 10^{-12}, may be interpreted as a rate of solution in the absence of chloride ions. This interpretation is supported by measurements in chloride-free solvents.

TABLE IV. RATES OF SOLUTION OF CUPROUS OXIDE IN SODIUM CHLORIDE–SODIUM NITRATE–BORATE BUFFERS AT 20° C. AND pH 7.88

		Rate of Soln., Moles Cm.$^{-2}$ Sec.$^{-1}$, × 10^{12}		
Molar Chloride Concn.	Molar Ionic Strength	Coating 1[a], agitation, 15 cm./min.	Coating 1[a], agitation, 144 cm./min.	Coating 2[b], agitation, 144 cm./min.
0.12	0.51	..	9	..
0.24	0.51	12	22, 22	8
0.36	0.51	18	40, 46, 48	15
0.48	0.51	30	59, 68	21
0.60	0.63	44	107	26
0.72	0.75	57	161	34
0.96	0.99	..	244	..

[a] Reduced to a standard sea water solution rate of 50 × 10^{-12}.
[b] Reduced to a standard sea water solution rate of 20 × 10^{-12}.

RATE OF SOLUTION IN CHLORIDE-FREE SOLVENTS

Measurements were made, in solutions of sodium nitrate containing 0.1 *M* borate buffer at pH 7.88 and agitation of 144 cm. per minute, on panels covered with coatings 1 and 2:

Ionic Strength	Rate of Soln., Moles Cm.$^{-2}$ Sec^{-1}, $\times 10^{12}$	
	Coating 1	Coating 2
0.03[a]	10	..
0.27	7	5
0.51	6	..
0.99	7	..

[a] Borate only.

The rate of solution, which does not vary much with ionic strength, is approximately equal to the value obtained by extrapolating the data of Table IV to zero chloride concentration. There are apparently two concurrent dissolution processes, one proportional to the square of the chloride concentration, and the other independent of it. The contribution of the latter, when the chloride concentration is that of sea water, is between 10 and 15%.

EFFECT OF IONIC STRENGTH

Comparisons were made of the rates of solution from coating 1 in pairs of solvents in which the chloride ion concentration was the same but the ionic strength, adjusted with sodium nitrate, was different. The results are given in Table V, which includes the ratio of the rate of solution at the given ionic strength in each case to that at ionic strength 0.51. This ratio decreases with increasing ionic strength from 0.15 to 0.5, and thereafter changes little.

Table V. Effect of Ionic Strength on Rates of Solution of Cuprous Oxide (Coating 1) in Sodium Chloride–Sodium Nitrate–Borate Buffers at pH 7.88 and Agitation of 144 Cm./Min.

Molar Chloride Concn.	Molar Ionic Strength	Rate of Soln.[a], Moles Cm.$^{-2}$ Sec.$^{-1}$, $\times 10^{12}$		
		At given ionic strength	At ionic strength of 0.51	Ratio
0.12	0.15	17	9	1.89
0.24	0.27	29	22	1.32
0.36	0.39	52	45	1.16
0.48	0.51	68	68	1.00
0.48	0.63	66	68	0.97
0.48	0.75	79	68	1.16
0.48	0.99	65	68	0.96

[a] Reduced to a standard sea water solution rate of 50×10^{-12}.

Although the data do not permit extrapolation to zero ionic strength, it can be seen qualitatively that the dependence of the rate of solution on ionic strength is similar to that of the activity coefficient of a uni-univalent salt (*4*).

COMPARISON OF DILUTED SEA WATER WITH ARTIFICIAL SOLVENTS

Measurements were made of the rates of solution from coating 1 in sea water diluted with distilled water to various extents.

Corrections for slight deviations from a pH of 7.88 were made as described above. The values are given in Table VI, together with the rates of solution in solvents of the same chloride concentration and ionic strength, estimated by multiplying the data of Table IV by ionic strength factors interpolated from Table V.

The rate of solution in the artificial solvent is in each case somewhat greater; it can be expressed approximately by the interpolation equation,

$$L_A = 6 + 1.2\, L_S$$

where L_S = rate of solution in diluted sea water

This difference may be due to a retarding effect of some constituent of sea water. It is small enough so that conclusions concerning the mechanism of the reaction which are drawn from the data in artificial solvents are probably applicable to sea water also.

TABLE VI. RATES OF SOLUTION OF CUPROUS OXIDE (COATING 1) IN DILUTED SEA WATER AND IN ARTIFICIAL SOLVENTS OF THE SAME CHLORIDE CONCENTRATIONS AND IONIC STRENGTHS

Molar Chloride Concn.	Molar Ionic Strength	Rate of Soln.[a], Moles Cm.$^{-2}$ Sec.$^{-1}$, × 10^{12}		
		Diluted sea water	Artificial solvent	
			Measured[b]	Calcd.[c]
0.12	0.16	13	16	21
0.24	0.32	17	27	26
0.36	0.48	33	46	46
0.48[d]	0.63	50	66	66

[a] Reduced to a standard sea water solution rate of 50 × 10^{-12}.
[b] From Tables IV and V.
[c] Calculated as 6 + 1.2 L_S
[d] Undiluted sea water.

DISCUSSION

Under conditions of high agitation, the rate of solution of cuprous oxide is proportional to the hydrogen ion concentration and a linear function of the square of the chloride ion concentration. This is the relationship which would be expected if the process

$$\tfrac{1}{2}Cu_2O + H^+ + 2Cl^- = CuCl_2^- + \tfrac{1}{2}H_2O$$

is the rate determining step in dissolution. The dependence of rate of solution on ionic strength is also qualitatively in agreement with this mechanism. Following the Scatchard treatment (*11*), if one positively and two negatively charged univalent ions approach to form a complex with a single negative charge, the effect of ionic strength on the rate of reaction is the same as for the approach of two oppositely charged univalent ions—i.e., the same function as for the activity coefficient of a uni-univalent electrolyte. Although this relation was derived for reactions in solution, it should hold also at a solid-liquid interface. It may be concluded that the formation of $CuCl_2^-$ is the rate determining step of the process which predominates in dissolution. It is possible that one hydrogen and one chloride ion approach, respectively, an oxygen and a copper atom adjacent on the cuprous oxide surface, and the collision of a second chloride ion results in detaching the complex.

As for the small contribution to dissolution which is independent of chloride concentration, this process may involve reaction of the surface with hydrogen ions alone and result in liberation of free cuprous ion.

Under conditions of low agitation where diffusion presumably limits the rate of reaction, the same dependence upon the first power of hydrogen and second power of chloride ion concentration still holds approximately. It may be tentatively concluded that the rate of diffusion depends on the concentration of the ionic species $CuCl_2^-$ at the surface of the solid cuprous oxide and that this is proportional to $(H^+)(Cl^-)^2$. It is then necessary to conclude that the higher complex $CuCl_3^{--}$ is formed more slowly.

ESTIMATION OF SPECIFIC RATE CONSTANT. For coating 1, which contains 90% of cuprous oxide (a volume fraction of 0.65), it may be assumed that the area of solute exposed on the surface does not differ greatly from the panel area itself; it will tend to be lower because of the presence of the binder, but this will be counterbalanced by the irregularity of the surface with consequent excess area. Probably the representative value of 50×10^{-12} moles cm.$^{-2}$ sec.$^{-1}$ in sea water at pH 7.88 is of the same order of magnitude as the rate of solution from a plane surface of cuprous oxide. If the exponential factor with the activation energy is introduced, we have for the rate of solution at pH 7.88 and a chloride concentration of 0.48 *M* the value $0.040\ e^{-12{,}000/RT}$ moles cm.$^{-2}$ sec.$^{-1}$.

RELATION OF SOLUBILITY TO ANTIFOULING EFFECTIVENESS. The proved efficacy of cuprous oxide in antifouling paints indicates that its moderately low solubility and rate of solution permit the control of its leaching rate from a paint without undue difficulty. The selection of a toxic with these characteristics is the first step toward the resolution of the dilemma of Young (*12*). The solubility of cuprous oxide will be compared with those of other antifouling toxics in the second paper of this series (*3*).

ACKNOWLEDGMENT

The interest of Captain H. A. Ingram, U.S.N., in initiating this study is gratefully acknowledged. The writers are indebted to the Bakelite Corporation for supplying the insoluble binders used in compounding the cuprous oxide.

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FREE-FALL CORING TUBE: A NEW TYPE OF GRAVITY BOTTOM SAMPLER

BY M. JUUL HVORSLEV AND HENRY C. STETSON

CONTENTS

	Page
Abstract	935
Introduction and acknowledgments	936
General principles of free-fall coring tube	938
Theoretical considerations	938
Forces and deformations during coring	940
Construction details	943
General statement	943
Coring tube	943
Drive weight with check valve and guide vanes	944
Release mechanism	944
Coring operations	946
Results	947
Resumé	949
References cited	949

ILLUSTRATIONS

Figure	Page
1.—Principal elements and steps of operation of the free fall coring tube	937
2.—Velocity, energy, and duration of fall for a 1000-pound sampler	940
3.—Release mechanism for free-fall sampler	945
4.—Diagram of core no. 9-1941	948

Plate	Facing page
1.—Construction details	935
2.—Experimental sampling in varved clay	946
3.—Handling the coring tube on shipboard	947
4.—Effect of coring tube on different types of bottom	948

ABSTRACT

A new method of operating gravity-coring tubes has been developed and tested. By means of a pilot weight and release mechanism, the coring tube with drive weight and guide vanes is released at a predetermined distance above the sea bottom and allowed to drop freely through the water. It thereby gains considerable velocity and momentum, and the energy available for forcing the tube into the sediments may be increased in this manner. This method of operation has proved to be especially valuable in coring firm sediments, in which hitherto it has been difficult to obtain a satisfactory depth of penetration with a coring tube whose downward velocity is governed by the safe speed at which a cable may be payed out. Two coring tubes of this type have been built for the Woods Hole Oceanographic Institution, and cores of bottom sediments obtained in the North Atlantic Ocean at depths up to 2250 fathoms. The general theory and details of construction and operation and some of the results obtained are described.

INTRODUCTION AND ACKNOWLEDGMENTS

The coring tubes used in early explorations of the bottom sediments of the oceans were all of the simple gravity type. The coring tube with attached iron or lead weights was lowered at the maximum safe speed at which the cable may be unreeled, generally 3 to 5 ft./sec. This method is still employed with many of the currently used coring tubes, and it provides satisfactory penetration of the tube into fairly soft but not into coarse or somewhat consolidated sediments. As will be shown later, the kinetic energy gained by a velocity of 3 to 5 ft./sec. constitutes only a very small part of the energy used in forcing the tube into the sediment. By far the largest part of the energy is the potential energy furnished by the weight of the tube and attached drive weights, and this weight is limited by the capacity of the winch and the strength, length, and weight of the cable paid out, and the additional force required to withdraw the tube from the sediment.

To supply additional energy, required for greater penetration into firm sediments, Piggot (1936; 1941), developed a sampler in which the coring tube is attached to a short, heavy gun barrel and is forced into the sediment by means of explosives. In 1935 he carried out the first deep-water trials from the research vessel ATLANTIS in the canyons from the Hudson Gorge, south. Subsequenty, two of these coring tubes were built for the Woods Hole Oceanographic Institution and were used successfully, superseding the weighted tubes which had formerly been employed. The 10-foot cores that have been obtained with this instrument by Piggot himself as well as by others fully demonstrate its superiority over anything that had previously been developed, and the cores have proved of the greatest value. Thanks are due Piggot for supervising the construction of these instruments for the Oceanographic Institution and for assistance on the first trip on which they were used.

Varney and Redwine (1936–1937) attempted to obtain additional energy by utilizing the hydrostatic pressure as a driving force, but the apparatus has not been developed beyond the experimental stage, and, as far as the authors know, a practical and satisfactory solution was not found.

Pettersson and Kullenberg (1940; 1941) have devised a coring tube in which a partial vacuum is created over the core so that the outside hydrostatic pressure will help to force the sediment into the tube and thereby also decrease its resistance to penetration. This coring tube has been used in the Swedish fiords, and penetrated up to 8.5 m in soft and 6.8 m in firm bottom. The corresponding core lengths were 8.5 and 4.2 m; the longest cores ever taken in a single drive by any method. This is particularly significant in view of the fact that the depth of the water over the firm bottom was only 25 m and the hydrostatic pressure consequently small. Details regarding the method used to force the tube into the sediment, such as weight and velocity of descent, are not given in the papers. Neither is the character of the sediment described in detail, and it is therefore difficult to compare the conditions with those along the North Atlantic coast of America.

The simplest method of obtaining additional energy without unduly increasing the weight of the sampler is to increase its downward velocity and thereby its kinetic energy. Emery and Dietz (1941), and Shepard and Emery (1941) increased velocities by allowing the winch to run on the brake for the last 300 feet of the descent. Velocities up to 20 ft./sec. and penetrations up to nearly 17 feet in soft materials

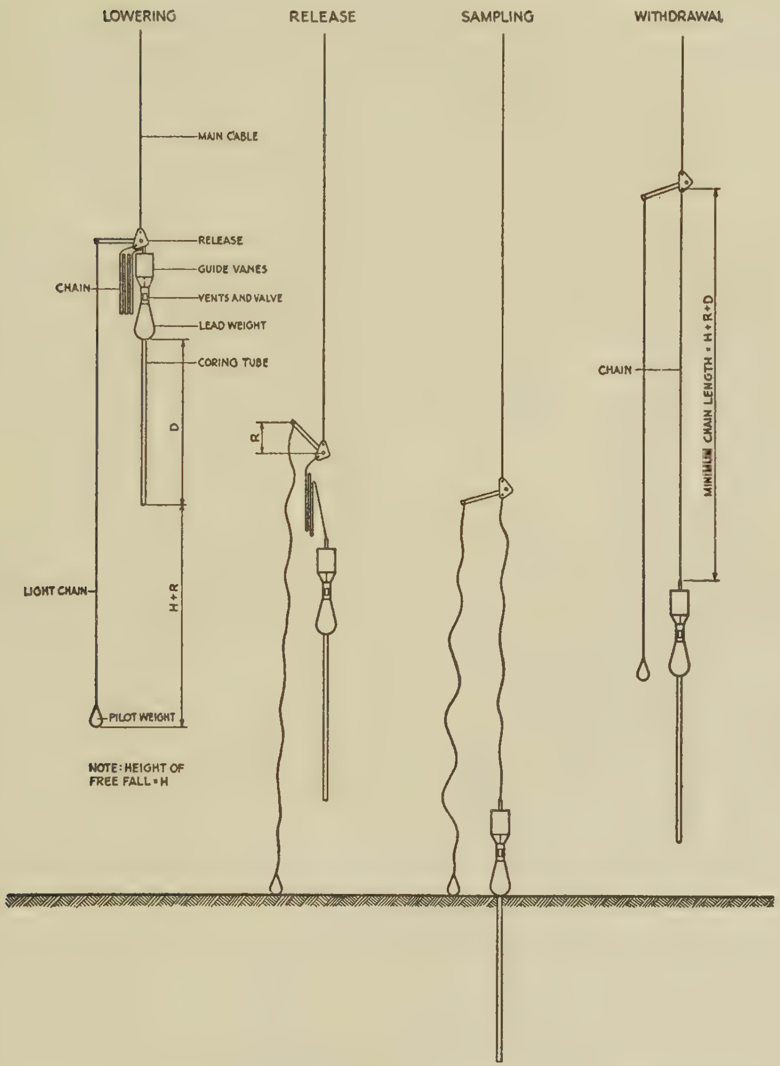

LOWERING
RELEASE
SAMPLING
WITHDRAWAL
MAIN CABLE
RELEASE
GUIDE VANES
CHAIN
VENTS AND VALVE
LEAD WEIGHT
CORING TUBE
D
R
LIGHT CHAIN
H+R
PILOT WEIGHT
NOTE: HEIGHT OF FREE FALL = H
CHAIN
MINIMUM CHAIN LENGTH = H+R+D

Figure 1.—*Principal elements and steps of operation of the free-fall coring tube*

were thereby attained, but the depth of penetration in coarse or stiff sediments was still relatively small.

The method of obtaining additional velocity by letting the winch run out on the brake alone could not be used in the case of the heavier equipment on Atlantis, for which the maximum safe speed at which the wire can be payed out is about 3 ft./sec. In an effort to overcome this difficulty of attaining the requisite velocities, and to develop a sampler capable of deep penetration which could be operated by crews inexperienced in the handling of explosives, the writers held many discussions of the problems involved in the design of a suitable sampler, and of the limitations which are necessarily imposed by its use on shipboard. As a result, a coring tube was developed which can be released from the main cable at a predetermined distance above the bottom, and thereafter is allowed to fall freely through the water for the remaining part of its descent. Through the aid of a grant from the Penrose Bequest of The Geological Society of America, two free-fall coring tubes were built for the Woods Hole Oceanographic Institution in 1940. Hvorslev is responsible for the general theory of the apparatus, the authors collaborated closely in its detail design, and Stetson supervised the preliminary experiments and subsequent coring operations.

This paper was prepared in all essential details in 1941, but its completion and publication was postponed because of priority of other work, and in the hope of making further experiments and improvements. Further experiments had to be abandoned because of the war, and, since considerable time may still elapse before they can be resumed, it was thought advisable to give an account of the new coring tube in its present state of development. A detailed description of the cores obtained, from a geological standpoint, will be given in another paper.

GENERAL PRINCIPLES OF THE FREE-FALL CORING TUBE

The principal elements and steps in the operation of a free-fall coring tube are shown in Figure 1. The three principal parts of the sampler are: (1) the coring tube proper, (2) a streamlined drive weight with check valve and guide vanes, and (3) a release mechanism with a lever, to the long arm of which is attached a light cable or chain with a pilot weight.

The coring tube and drive weight are permanently attached to the base plates of the release mechanism by means of a chain, hereafter called the coring-tube chain. During lowering, this chain is bunched up and lightly secured with twine to the drive weight, which is attached to the short arm of the release lever and balanced by the pilot weight. The length of the pilot weight chain is such that the vertical distance between the pilot weight and the cutting edge of the coring tube is a little greater than the desired height of the free fall.

When the pilot weight strikes the bottom, the balancing force on the lever is eliminated, and the drive weight with the coring tube is released and falls freely, breaking the twine and straightening out the bunched up chain behind it. The assembly is kept vertical by the guide vanes. The winch is stopped immediately after the release of the drive weight, and the entire assembly is withdrawn after allowing sufficient time for the free fall and the penetration of the coring tube into the bottom sediment.

THEORETICAL CONSIDERATIONS

The force with which the coring tube strikes the bottom depends not only on its weight and downward velocity but also on the elastic properties of the sediments, and it is therefore difficult to evaluate. For the purpose of estimating the influence of the velocity, it is easier to consider the energy. The total energy, E, expended from the moment the coring tube strikes the bottom until it comes to rest after a depth of penetration, D, is the sum of the potential and kinetic energy, or:

$$E = W\left(D + \frac{v^2}{2g}\right) = W(D + h),$$

where W is the weight of the coring tube and drive weight, v its velocity at the start of the penetration, and g the acceleration of gravity. The height $h = v^2/2g$ may, borrowing a term from hydraulics, be called the velocity head. Values of h for increasing values of v are as follows:

$v = 3$	5	10	20	30	40	50	60	ft./sec.
$h = 0.14$	0.39	1.55	6.22	13.99	24.87	38.86	55.96	ft.

For the usual safe unreeling speed of 3 to 5 ft./sec., the value of h and thereby the kinetic energy constitutes only a small fraction of the potential energy, even when a penetration of only a few feet is obtained, whereas it may be several times the potential energy for large values of v. This increase in available energy with v is still more striking considering that the higher velocities also produce a greater penetration and thereby make more potential energy available. For example, when a conventional gravity-coring tube is lowered at a speed of 5 ft./sec. and penetrates 4 feet into the bottom, the total energy expended is $E = W \times 4.39$, but if by a free fall of about 30 feet the velocity is increased to 40 ft./sec. (*see* Figure 2) and a penetration of 10 feet is obtained, then the total energy expended is $E = W \times 34.87$, or more than eight times as much as for the conventional gravity-coring tube.

The problem of determining the velocities of a body freely falling through air or water was solved long ago, and the solution can be found in various textbooks and handbooks. If gravity were the only force acting upon the body, the velocity would increase according to the formula $v = \sqrt{2gH}$, where H is the height of the fall. However, the falling body meets resistance in the form of fluid friction and hydrostatic pressure differences caused by the motion; this resistance increases with the square of the velocity, and when it equals the weight of the body the maximum or terminal velocity, v_t, is reached and remains constant during any further fall. The terminal velocity is determined by the formula:

$$v_t^2 = \frac{2\,g\,W}{c \cdot \gamma\,A},$$

where c is a dimensionless coefficient called the coefficient of drag, γ is the unit weight of water or 64 lbs./cu.ft. for sea water, and A is the maximum cross-sectional area of the body. The drop, H, required to develop the velocity v is determined by:

$$H = \frac{v_t^2}{2g}\, ln\, \frac{v_t^2}{v_t^2 - v^2},$$

and the duration of this fall by:

$$T_f = \frac{v_t}{g}\, ln \left[e^{gH/v_t^2} + \sqrt{e^{2gH/v_t^2} - 1} \right]$$

In deriving these formulas it is assumed that the velocity at the start is zero; that is, the unreeling speed of the cable is not taken into consideration, but this speed is generally so small that its influence is negligible. Computation of the time required for penetration (Tp) of the coring tube is more difficult, since not only the depth of penetration but also the penetration resistance and its variation with depth must be known, and this resistance varies with both the character and the sequence of the strata. However, the formula:

$$T_p = \frac{2D}{v}$$

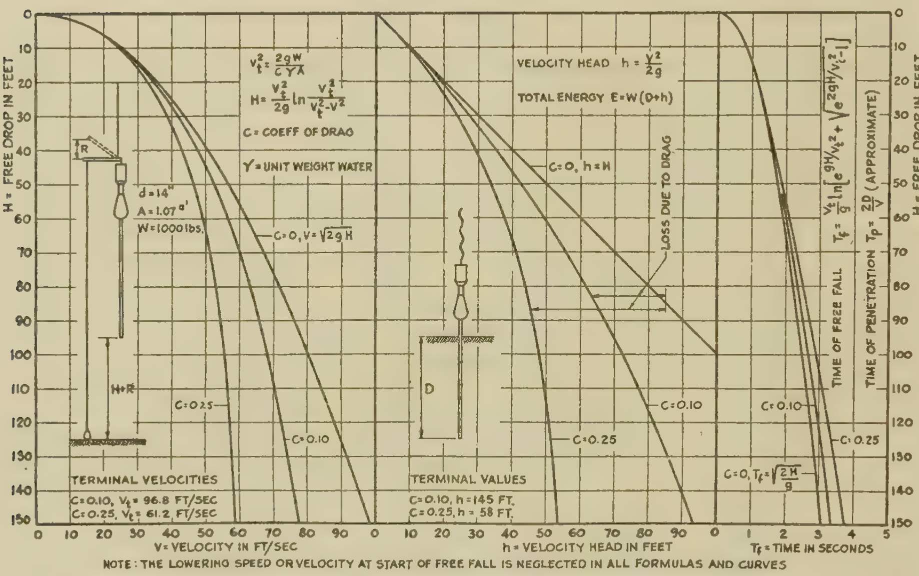


FIGURE 2.—*Velocity, energy, and duration of fall for 1000 lbs. sampler*

will give results sufficiently accurate for the purpose here and is on the safe side when D is taken as the total length of the coring tube proper.

The velocities, velocity heads, and the duration of the free fall have been computed by means of the above formulas for the coring tube built for the Woods Hole Oceanographic Institution, and are given graphically in Figure 2 as a function of the free fall, H. The weight of the coring tube and drive weight is approximately 1000 pounds, and the maximum diameter of the latter is 14 inches, corresponding to a cross-sectional area $A = 1.07$ sq. ft. The coefficient of drag has not been determined, but it was estimated to be between $c = 0.10$ and $c = 0.25$. It will be seen from these curves that the values of c has very little influence on the values of T_f within the practical range of the free drop. The influence of c on v and h is insignificant for small values of H, but it increases rapidly with H and is very great in case of the terminal values v_t and h_t.

FORCES AND DEFORMATIONS DURING CORING

Before describing the design details of the coring tube, it is desirable to review briefly what happens when the tube is forced into the sediment. Some of the principal conceptions and the photographs presented in this section are the results of experiments carried out by Hvorslev (1940a) for the Committee on Sampling and

Testing, Soil Mechanics and Foundations Division, American Society of Civil Engineers. Other experiments have also been made by Piggot (1941) and Emery and Dietz (1941).

When the coring tube is forced into the sediment, an amount of material corresponding to the volume of the walls of the coring tube and its liner is pushed aside. During the first part of the coring operation, when the friction between the core and the tube still is small, some of the displaced material may possibly be forced into the tube, thereby causing a distortion and an increase in thickness of the individual strata of the core. In experiments with fairly thick-walled coring tubes, forced slowly into soft material, an increase in thickness of more than 50 per cent for the upper strata of the core has been observed; but it was also noted that the entrance of excess material decreased to a small amount when the velocity of penetration exceeded a few feet per second. Nevertheless, it is desirable to reduce the wall thickness of the coring tube and its liner to the minimum consistent with structural requirements, not only to avoid entrance of excess material but also to decrease the resistance to penetration.

Entrance of soil into the coring tube is hindered in part by the hydrostatic pressure on top of the core and in part by the friction between the core and the walls of the liner. The hydrostatic pressure over the core is counteracted by the pressure in the pore water below the coring tube, but adequate vents must be provided to prevent any material increase in the pressure over the core as it enters the tube and expels the water. At high velocities of penetration the vents should have an area at least equal to that of the core and should also be streamlined (Piggot, 1936).

The friction between the core and the liner is transmitted to, and increases the pressure on, the material below the coring tube. The friction and pressure increase with the length of the core, and may, after a certain length of core is reached, cause considerable compaction of loose and partially saturated subaerial soils thereby shortening the core. However, it is doubtful that any material compaction will occur during coring operations on the ocean bottom. The sediments are here fully saturated, and only a negligible amount of water can be forced out of the material during the short period required for full penetration of the coring tube. On the other hand, when the increase in pressure below the coring tube reaches a certain value, it will cause a downward deflection and a consequent stretching and decrease in thickness of the strata before they enter the tube (Pl. 2, fig. 1). This downward deflection and stretching and not actual compaction is generally the factor responsible for a shortening of the core.

A moderate downward deflection and decrease in thickness of the strata before they enter the tube may occur without causing any visible distortion of the strata in the core, but, when the deflection becomes so large that it causes a reduction in thickness greater than 5 to 15 per cent, it will also produce a downward curvature of the strata (Pl. 4, fig. 2). The inside friction may in certain cases reverse this curvature close to the cylindrical surface of the core. An upward curvature of the strata over the entire cross section is occasionally observed in the upper part of a core. Such a curvature may be caused either by the inside friction or by entrance of excess material and a consequent increase in thickness of the particular strata.

In brittle materials the increase in pressure below the tube may cause shear failures and abrupt displacements (Pl. 4, fig. 3 *upper part,*) instead of a uniform deflection and decrease in thickness. It should be noted that some relatively soft materials act like a brittle substance when subject to sudden stress changes and deformations. In sediments consisting of thin strata of varying firmness, the softer strata will often be subject to a greater decrease in thickness than the firm strata (Pratje, 1934; 1936). When the deformations become large, the major part of the soft strata may be pushed aside while the firm strata are broken up and mixed with the remnants of the soft strata (Pl. 4, fig. 3, lower part). The core will ultimately reach such a length that the corresponding inside friction prevents further entrance of material. A bulb or cone of sediment is then formed below the cutting edge (Pl. 2, fig. 2), and further penetration merely results in pushing the sediment aside as a solid bar would do.

To obtain long and relatively undisturbed cores, the inside friction must be reduced. This is accomplished (1) by keeping the inside surface of the liner absolutely smooth and clean (pitted and corroded tubes should not be used), and (2) by making the diameter of the cutting edge, D_e, slightly smaller than the inside diameter, D_s, of the liner, so that a small inside clearance, $(D_s - D_e)$, is produced. The inside clearance should, normally, be only large enough to compensate for the elastic expansion of the core as it enters the tube. If it is larger than that, the core will be deprived of lateral support; in stiff material this may again cause elimination of the inside friction and loss of the core during the withdrawal unless a core catcher is provided. Experiments on land have shown that an inside clearance in excess of 1.5 to 2.0 per cent of D_s often will cause loss of the core.

When an excessive inside clearance is used in soft or cohesionless materials, the core will slump and expand laterally until it is restrained by the liner, and the inside friction will then be re-established. Slumping may cause disturbance of the structure and a decrease in strength of the material; it cannot be permitted when undisturbed samples are desired, but it will not seriously impair the value of cores taken solely for geological examination. The larger inside clearance will unquestionably help to produce longer cores and has been used successfully in many instances, especially when a core catcher also is provided. However, a lateral expansion, in excess of a purely elastic one, will cause a shortening of the core. If the inside clearance is $(D_s - D_e) = m\, D_s$, and it is assumed that there is no volume change of the material, then the shortening of the core length, $m\, L$, is given by

$$\mathrm{m} = 2\mathrm{n} - \mathrm{n}^2,$$

or roughly twice the inside clearance when the latter is small. Clearances up to 10 per cent have been used in some coring tubes and may, disregarding volume changes, cause a shortening of the core up to 19 per cent. To the shortening caused by slumping of the core must be added the effect of a possible downward deflection, stretching, and reduction in thickness of the strata before they enter the coring tube.

The above-mentioned causes of shortening of the core in certain materials may be counteracted by a liberation and expansion of gases dissolved in the pore water. At the hydrostatic pressure existing at great depths considerable amounts of various gases may be dissolved in the pore water, especially in sediments containing organic materials, or where the ground-water flow has passed through such deposits. When the core is brought to the surface, the hydrostatic pressure is reduced to, and, on account of capillary action, even below atmospheric pressure. The dissolved gases are then partially liberated and expand, thereby increasing the length of the core. An increase in length after recovery amounting to several per cent has been observed for cores taken at such shallow depths as 25 to 50 feet in New York Harbor. The liberation of gases takes place rather slowly and may continue for a considerable period of time after the core is brought to the surface. It is therefore advisable to measure the core length accurately immediately after the coring tube is brought to the surface, in order to be able to determine the amount of any subsequent expansion caused by liberation or gases, or any shrinkage caused by drying.

CONSTRUCTION DETAILS

GENERAL STATEMENT

The detail design of the sampler was to a large extent governed by available materials and equipment. Because of some uncertainty with respect to the energy required to penetrate the very stiff bottom sediments of the Atlantic continental slope, and also because of some doubt with regard to the vertical stability of the sampler during the free fall, it was decided to make the drive weight as heavy as possible, considering the strength of the wire and the capacity of the winch on Atlantis.

CORING TUBE

The coring tube proper (Pl. 1) consists of a section of seamless steel tubing, reamed to an internal diameter of 2.200 inches to provide a sliding fit for a liner of brass tubing 10 feet 00 inches long, with an outside diameter of 2.000 inches and a wall thickness of 0.025 inch. The upper half of the steel tubing has an outside diameter of 2.500 inches; the diameter of the lower half is gradually decreased to 2.200 inches, which dimension is maintained for the lower 2 feet of the tube. It was hoped that this reduction in the outside diameter, besides lessening the danger of excess material entering, would increase the depth of penetration, at least into deeper-lying, firm strata. It would have been desirable to maintain the smaller outside diameter over the entire length of the tube, and the use of a tube with a uniform outside diameter of 2.250 inches was considered. However, it might not have had sufficient strength to withstand the bending moments to which it would be subjected during the withdrawal, in case the ship drifts during the coring operation, thereby causing considerable wire angle.

Close to the cutting edge, the outside diameter is again increased slightly so that it will provide a small outside clearance and reduce the friction between the lower part of the tube and the surrounding material. The consequent increase in wall thickness is also desirable to counteract the weakening effect of the threads for the cutter. The increased diameter of the bulb undoubtedly does decrease the outside friction, but it also increases the end resistance and should, therefore, be small when the tube is to be used in stiff materials, and perhaps entirely eliminated in dense, cohesionless sediments.

Screwed into the lower end of the tube is a sharp, hardened cutter with an inside diameter slightly smaller than that of the liner. Three interchangeable cutters, producing inside clearances of 1.0, 1.5, and 2.0 per cent, are provided.

DRIVE WEIGHT WITH CHECK VALVE AND GUIDE VANES

The upper end of the coring tube screws into a flange with another section of 2.5-inch tubing which supports the streamlined lead weights (Pl. 1; Pl. 3, figs. 1, 2). These weights were cast in sections for ease of handling. Above the weights is a short length of 5-inch standard pipe which serves as a connection to the guide vanes and as a housing for the check valve. This valve is intended to reduce the hydrostatic pressure over the core during the withdrawal, and it is streamlined in order to offer the least possible resistance to the water forced out of the tube during its penetration into the bottom. Vents in the valve housing provide easy access for inspection and cleaning.

Above the valve housing are four guide vanes, welded to a section of 2-inch standard pipe and to an encasing thin, steel cylinder. The latter protects the vanes during handling of the sampler, decreases the danger of fouling the trawl wire and chain, confines the slipstream, and increases the efficiency of the vanes. The eye bolt over he vanes was, in actual construction, replaced by a U-bolt welded to the 2-inch pipe. Several other minor changes and simplifications of the original design (Pl. 1) were made, and, when another sampler is to be built, both the drive weight and the guide vanes will probably be smaller. The total weight of the present drive weight with appurtenances and coring tube is approximately 1000 pounds.

RELEASE MECHANISM

The release mechanism consists of two roughly triangular base plates with stay bolts, spacers, and chain links, and with a bolt and bronze bushing which serves as a fulcrum for a lever with two unequal arms (Fig. 3). The drive weight with the coring tube is attached to the short arm, and a 100-pound pilot weight to the long arm of the lever. The lever arms are 1.5 and 30.0 inches long, or a ratio of 1 to 20. This means that a 2000-pound pull on the short arm is required to trip the lever, or approximately a factor of safety of two against an accidental release of the sampler. This factor of safety was considered sufficient to take care of a temporary decrease in the pull of the pilot weight, which may be caused by a sudden increase in the rate of descent during a heavy roll of the ship. Furthermore, the pilot weight is semi-streamlined to decrease the effect of such a change in the rate of descent. A safety pin through the base plates and the lever, locks the latter in position while the apparatus is being rigged and put over the side of the ship.

The sampler is attached to the base plates of the release mechanism by a $\frac{7}{16}$-inch chain so that it can be withdrawn from the bottom after the completion of coring. During lowering, this length of chain is bunched up and secured by light twine. Chain instead of wire was chosen for this purpose since wire must be coiled and

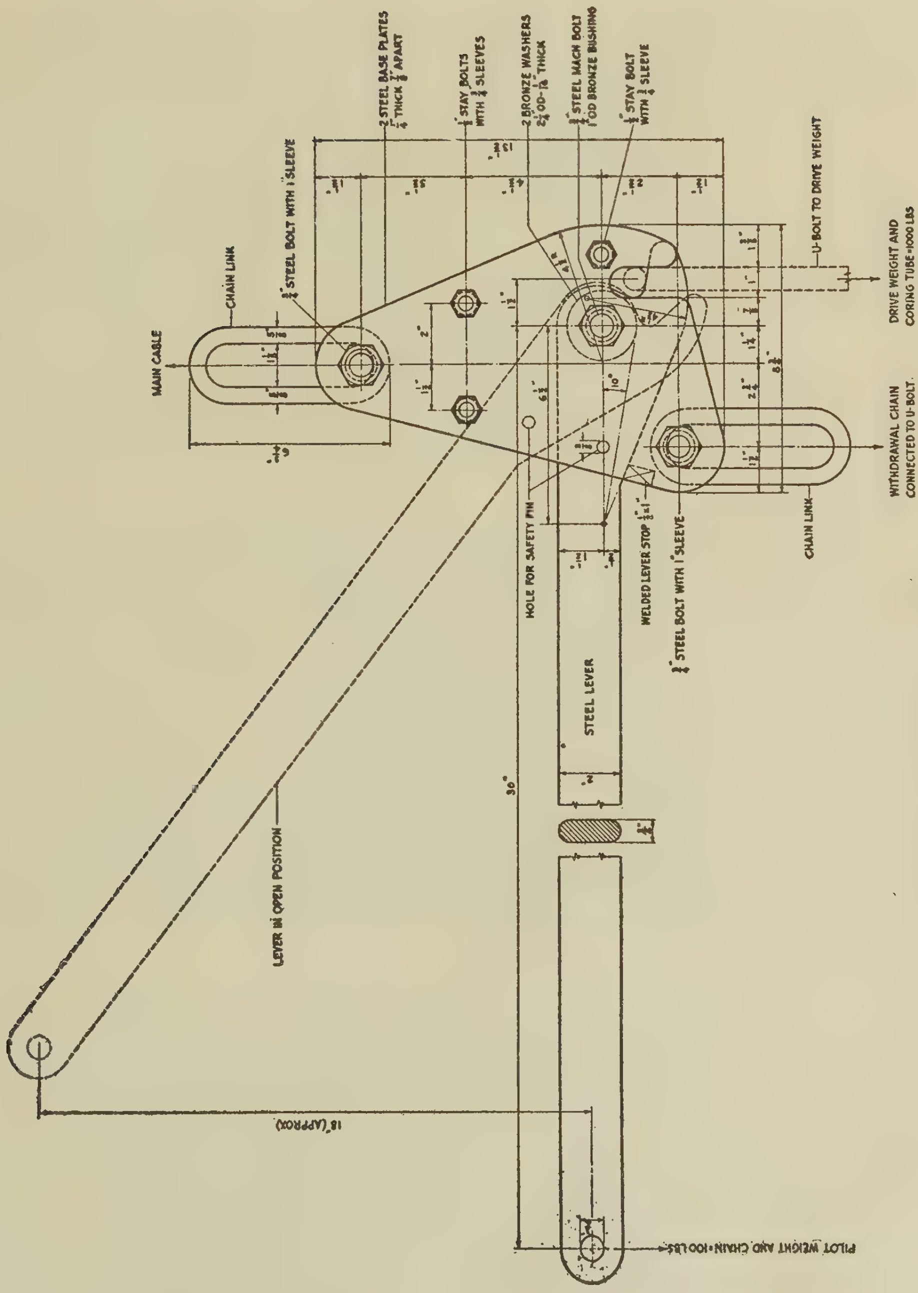

MAIN CABLE
CHAIN LINK
3/4" STEEL BOLT WITH 1" SLEEVE
2 STEEL BASE PLATES 1/4" THICK 7/8" APART
1/2" STAY BOLTS WITH 3/4 SLEEVES
2 BRONZE WASHERS 2 1/4" OD-1/16" THICK
3/4" STEEL MACH BOLT 1" OD BRONZE BUSHING
1/2" STAY BOLT WITH 3/4 SLEEVE
U-BOLT TO DRIVE WEIGHT
DRIVE WEIGHT AND CORING TUBE = 1000 LBS
WITHDRAWAL CHAIN CONNECTED TO U-BOLT
CHAIN LINK
3/4" STEEL BOLT WITH 1" SLEEVE
WELDED LEVER STOP 1/2"x1"
HOLE FOR SAFETY PIN
STEEL LEVER
LEVER IN OPEN POSITION
30"
18" (APPROX)
PILOT WEIGHT AND CHAIN = 100 LBS

FIGURE 3.—*Release mechanism for free-fall sampler*

would certainly foul and kink when rapidly straightened out during the free fall of the sampler. The light wire, by means of which the pilot weight was originally attached to the lever (Pl. 3, fig. 1) was later, and for the same reason, replaced by a $\frac{3}{16}$-inch chain.

CORING OPERATIONS

The free-fall coring tube was used on two trips with ATLANTIS during the summers of 1940 and 1941 and a total of 21 cores were taken. Coring operations were carried out along the continental slope from Hudson to Washington canyons and in the deep area southeast of the tip of Georges Bank. The depths varied from 100 to over 2250 fathoms, and the types of bottom sediments ranged from very stiff, silty clays with lenses of sand, gravel, and stones, to plastic clays.

In operation, the sampler is very simple and positive in its action. The assembly is rigged on deck with the length of the pilot-weight chain adjusted to the desired height of the free fall. The coring-tube chain is flaked down on deck and tied in a bunch, and the safety pin put in place. The sampler is then lifted horizontally on a hoisting boom and swung over the side by a wire sling spliced around the coring tube and the valve housing (Pl. 3, fig. 2). When suspended vertically from the trawl boom, the safety pin is pulled, and the sampler lowered away at the normal paying-out speed of the winch. When the moment of release and the start of the free fall is indicated on the dynamometer, the winch is stopped, and the withdrawal operation started at a very slow speed, after allowing sufficient time for the drop and the actual coring. On arrival at the surface the sampler is again picked up on the hoisting boom and swung aboard.

Because of wire angle it is very difficult, when working in deep water, to estimate how close any gear may be to the bottom, even when the amount of wire out and the depth of water is known. When excess wire is paid out after the bottom has been reached, it will lie in coils and tend to tangle and kink when taken in. The clear indication of the moment of release, which occurs in the case of the free-fall sampler, is, therefore, of the greatest advantage. The movement of the dynamometer, which is sharp and unmistakable, is due to a wave, caused by the sudden release of tension, travelling up the wire. The comparatively heavy weight of the sampler undoubtedly is a contributing factor. The moment of release was as clearly observed in 2200 fathoms as in 100, and, because of the conditions outlined above, presumably will be observed in 5000 fathoms. In contrast, the tension in the wire holding a standard gravity coring tube is decreased gradually while the tube is being driven into the bottom, and, in deep water, it is often difficult to determine when the coring operation is completed.

A possible rotation of the sampler during lowering was considered, thereby wrapping the pilot-weight chain around the sampler and preventing a proper release, or causing the coring tube to hit the pilot weight. However, difficulties of this kind were not encountered during any of the coring operations, nor did the roll of the ship ever cause a premature release. On one occasion, when a clutch failed, and the unreeling speed of the winch became too great, an accidental release occurred when the winch had to be brought up short on the brake. It only resulted in a heavy jar,

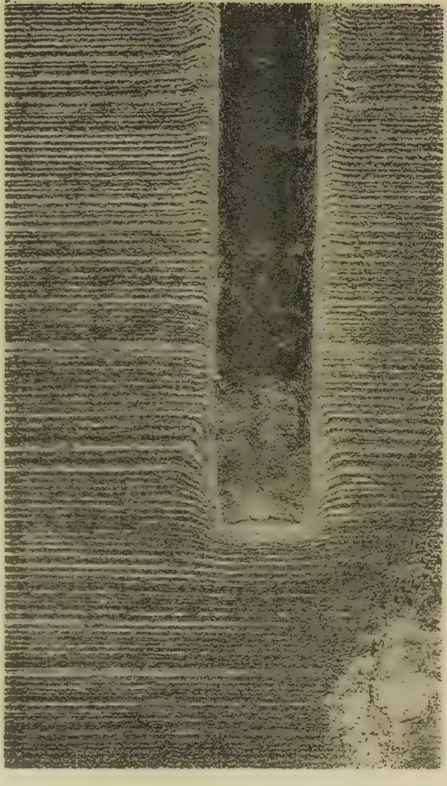
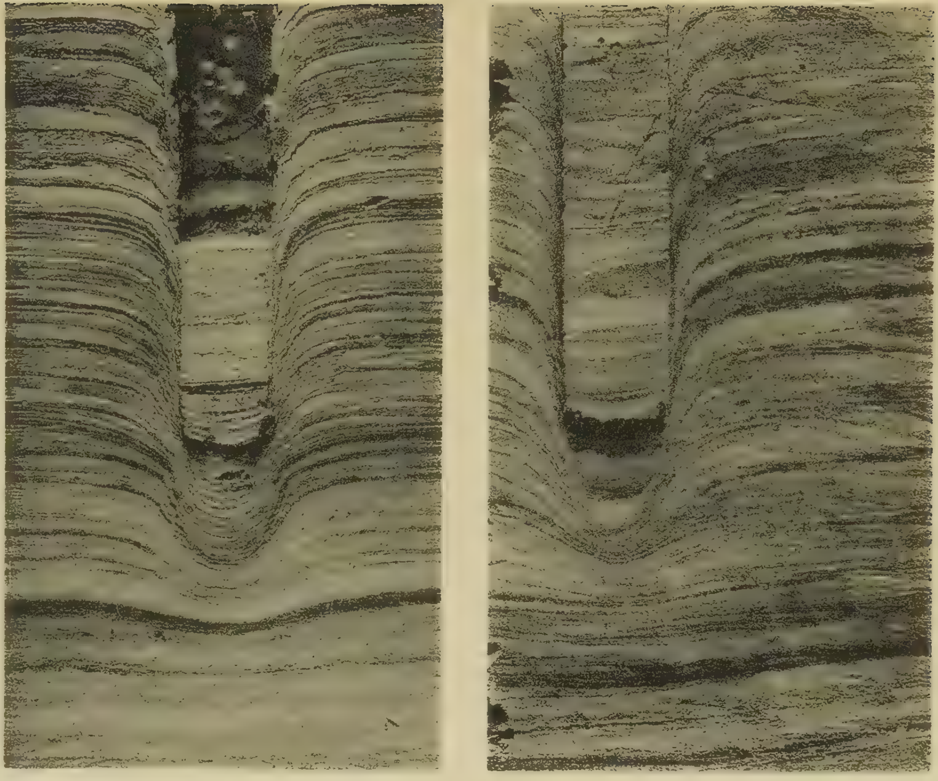


FIGURE 1. VERTICAL SECTION OF BORE HOLE
Showing start of downward deflection and stretching of soil layers below the bottom.



A

B

FIGURE 2. SECTION OF BORE HOLE AND LOWER PART OF SAMPLE
Showing formation of bulb or cone-shaped plug of sediment. A — Slow penetration. B — Fast penetration.

EXPERIMENTAL SAMPLING IN VARVED CLAY

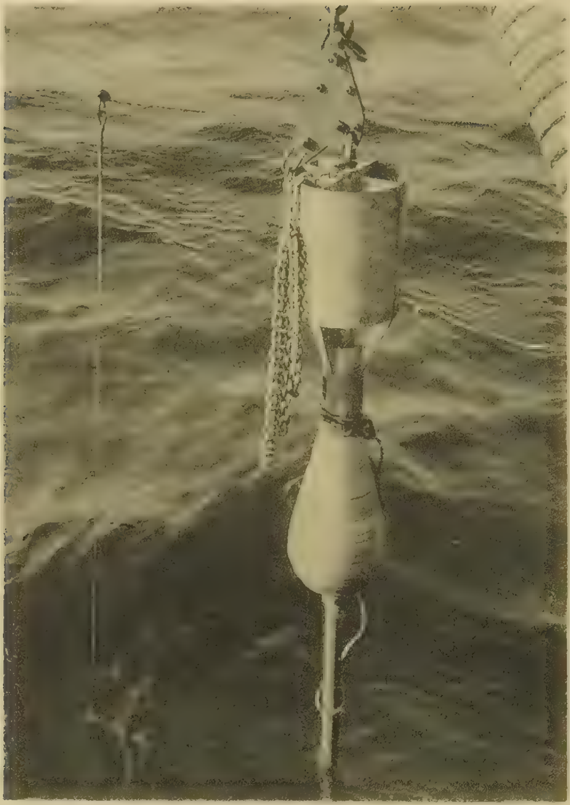


FIGURE 1. FREE FALL CORING TUBE READY FOR LOWERING.
Photo By F. B. Phleger

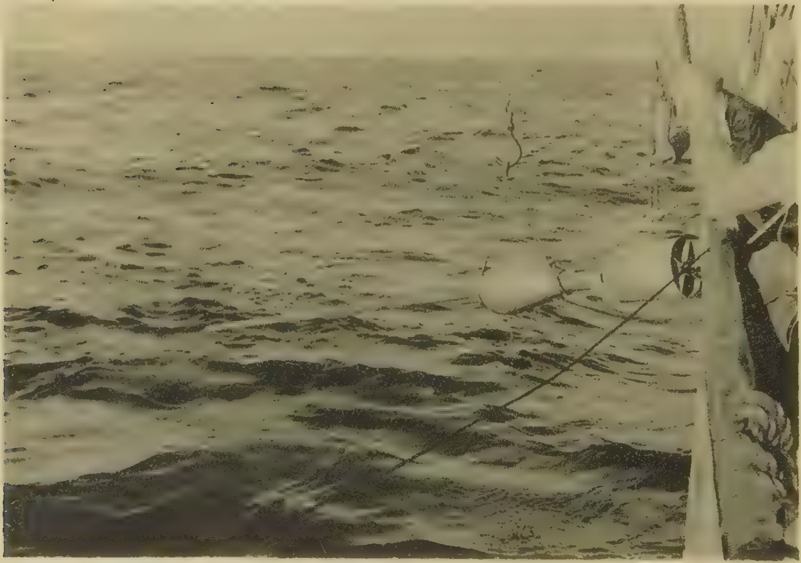


FIGURE 2. FREE FALL CORING TUBE BEING LIFTED ON BOARD AFTER CORING.
Photo By F. B. Phleger

HANDLING THE CORING TUBE ON SHIPBOARD

because of the cushioning effect of 2000 feet of wire which happened to be out at the time. Had it occurred with only a short length out, the wire might have parted.

RESULTS

Free drops of 7 to 10 feet were used, and, except in a very stiff and silty clay, sufficient energy was developed to force the 10-foot tube and a part of the drive weight into the sediment. Once the entire sampler was forced below the sea bottom. It is therefore evident that the available energy is sufficient to drive still longer coring tubes into the sediment for their full length, and more energy can be obtained by increasing the height of the free drop. Coring tubes with a length of 15 or 20 feet will be used in future operations. The stratification in all the cores was practically horizontal, which indicates that the sampler maintained its vertical position during the free fall.

A cutter with 2 per cent inside clearance was used in the first coring operation, and the entire core was lost. Cutters with 1 per cent inside clearance were employed on all subsequent stations. Even with this clearance the lower parts of three cores were lost during the withdrawal. In two cases this loss occurred when the coring tube was raised above the water, and possibly the check valve was not fully effective, since the rubber gasket had been damaged and a machined metal seat was used instead. Replacement of the metal plunger with a rubber or rubber-covered plunger, and other changes in the check valve, are contemplated, but its streamlined form will be maintained.

The length of the cores obtained varied from 28 to 113 inches, and a diagram of one of the longer cores is shown in Figure 4. The core contains strata of stiff clay, sand, gravel, and two large pebbles. A photograph of the boundary between a gravel and a stiff clay layer is shown (Pl. 4, fig. 1). The clay sections of the core have shrunk about 20 per cent, since it was allowed to dry approximately to the shrinkage limit in order to increase the color difference between the various materials. The climatic data based on the Foraminifera were furnished by Dr. Fred B Phleger. The original length of some of the cores may have been greater, and the entire core may have moved downwards in the tube during the withdrawal. However, the strata in the lower part of some of the cores show a distinct downward curvature (Pl. 4, fig. 2), and it is evident that the inside friction was great enough to cause a downward deflection, stretching, and reduction in thickness of these strata before they entered the tube. In the lower part of another core (Pl. 4, fig. 3) distinct shear planes are visible, and below these the sand strata are broken up and partially mixed with the remnants of the softer clay strata, the major part of which had been squeezed out. In one case a soil cone, similar to the one shown (Pl. 2, fig. 2) projected below the cutter, indicating that the limiting core length for the particular material, diameter, and inside clearance had been reached. As a whole, the length of the cores agrees fairly well with the lengths obtained in coring operations on land in similar materials, and with a tube having the same inside diameter and clearance. The cores (Pl. 4, figs. 1, 2, 3) are shown in the brass liners, which were halved longitudinally according to the method first devised by Piggot (1936).

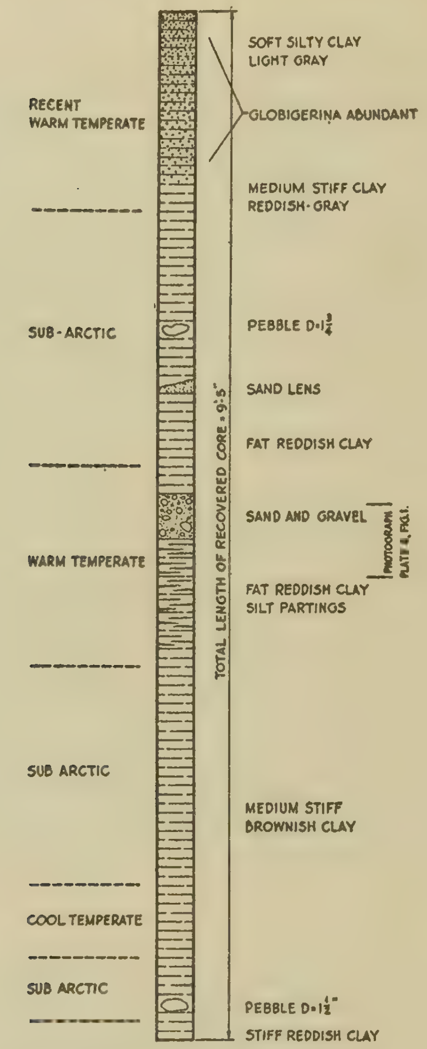

RECENT
WARM TEMPERATE
SUB-ARCTIC
WARM TEMPERATE
SUB ARCTIC
COOL TEMPERATE
SUB ARCTIC
SOFT SILTY CLAY
LIGHT GRAY
GLOBIGERINA ABUNDANT
MEDIUM STIFF CLAY
REDDISH-GRAY
PEBBLE D=1$\frac{3}{4}$
SAND LENS
FAT REDDISH CLAY
SAND AND GRAVEL
FAT REDDISH CLAY
SILT PARTINGS
MEDIUM STIFF
BROWNISH CLAY
PEBBLE D=1$\frac{1}{2}$"
STIFF REDDISH CLAY
TOTAL LENGTH OF RECOVERED CORE = 9'-5"
PHOTOGRAPH
PLATE 4, FIG. 1.

FIGURE 4.—*Diagram of core No. 9-1941*

N. lat. 40° 41′, W. long. 64° 55′, depth, 2250 fathoms. Climatic data from foraminifera identified by F. B Phleger

Undoubtedly much longer cores can be obtained by using a larger inside clearance. In addition, the brass liners will be replaced by newly developed, thin-walled, plastic tubing, which is transparent, easier to cut, and has a much smaller coefficient of friction than brass. An increase of the inside diameter of the coring tube will likewise permit the taking of longer cores, and sufficient energy is available to force the larger tubes into the sediment. However, these changes will increase the danger of losing the sample during the withdrawal, and it may become necessary to use a core catcher. A simple and efficient type has been developed by Emery and Dietz (1941).

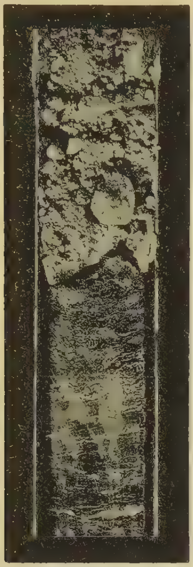


Figure 1. Section of Core No. 9-1941
Showing layers of gravel and firm red clay. N. Lat. 40° 41′, W. Long. 64° 55′, depth 4120 meters.

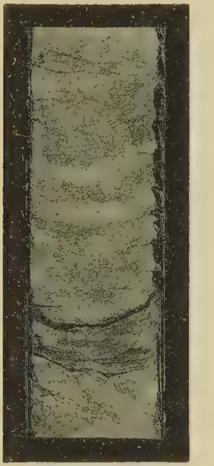


Figure 2. Bottom Section of Core No. 1-1941
Showing downward curvature of very stiff, silty clay strata. N. Lat. 40° 10′, W. Long. 68° 30′, depth 550 meters.

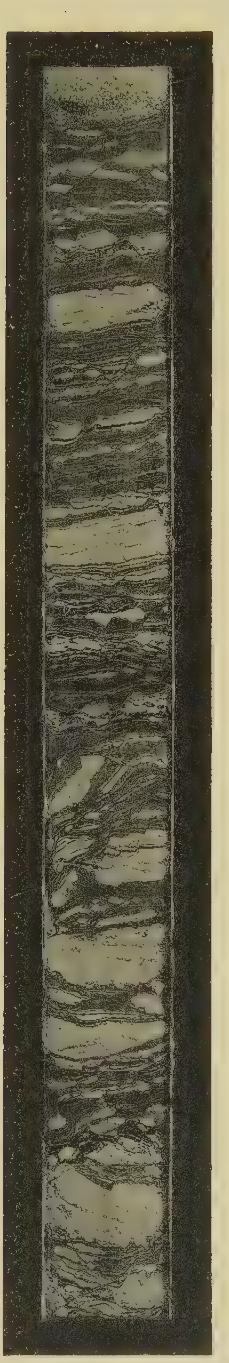


Figure 3. Lower Section of Core No. 7-1941
With thin layers of sand, silt and reddish clay. Top, shear planes and displacement. Bottom, distortion, breaking up and mixing of layers with clay partially squeezed out. N. Lat. 40° 34′ W. Long. 65° 02′, depth 4150 meters.

EFFECT OF CORING TUBE ON DIFFERENT TYPES OF BOTTOM

RESUMÉ

The practical tests with the free-fall coring tube have demonstrated that the proposed method of increasing the available energy of a gravity-coring tube is entirely feasible. The apparatus is simple in construction and easy, flexible, and reliable in operation. The method is independent of the design of the coring tube proper, and the proposed apparatus can be used without change at any ocean depth.

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FORAMINIFERA OF TWO SUBMARINE CORES FROM THE NORTH ATLANTIC BASIN

BY FRED B PHLEGER, JR. AND WALTER A. HAMILTON

CONTENTS

Page
Abstract 951
Introduction 952
Location of the cores 952
Method of study 952
The Foraminifera 956
 General statement 956
 Distribution of certain Foraminifera 957
Core faunas 959
 Core 7-41 959
 Core 9-41 959
Size distribution 960
Discussion 960
 General statement 960
 Interpretation of core faunas 961
  Temperature changes 961
 Size trends 963
  Pelagic species 963
  Benthonic species 964
Future work 964
Conclusions 964
References cited 965

ILLUSTRATIONS

Figure Page
1. Mean size groups of species in Core 7-41 955
2. Mean size groups of species in Core 9-41 956
3. Approximate relative water temperatures indicated by the foraminiferal faunas in the cores 962

Plate Facing page
1. Percentage frequency groups of species of Foraminifera in the core samples 964

ABSTRACT

The Foraminifera of two submarine cores from the basin of the western North Atlantic have been examined. Vertical faunal variations suggest two sub-Arctic faunas separated by a warm-temperature fauna, and these are beneath the present warm-temperate fauna. The Arctic faunas are interpreted as representing the two latest substages of the Wisconsin. A post-Wisconsin fauna in one core suggests warmer surface waters than at present.

Continuous sampling and quantitative study of the faunas are the most feasible methods for study of core faunas. A method of studying sizes of Foraminifera is described, and a possible correlation between sizes and ecologic factors is indicated.

INTRODUCTION

Foraminifera of two submarine cores from the western North Atlantic have been studied quantitatively to determine the frequency and size distribution of each species. The purpose of this study is: (1) to determine the environmental changes represented by the core Foraminifera in this area; (2) to examine the cores by a continuous sampling method in order to note detailed vertical changes of the faunas in the cores and determine the value of continuous sampling as compared with other methods; (3) to study size distribution, its variation in the cores, and its possible application to studies of core Foraminifera.

LOCATION OF THE CORES

The two cores studied are from a series of nine cores obtained by H. C. Stetson and the authors during the summer of 1941 from the research ship ATLANTIS, belonging to the Woods Hole Oceanographic Institution. They were taken south of the eastern end of Georges Bank, from near the edge of the Atlantic basin at that place. The locations and depths are as follows:

Core	*N. Lat.*	*W. Long.*	*Depth*	*Length of Core*
7-41	40° 34′	65° 02′	4150 m	188 cm
9-41	40° 41′	64° 55′	4120 m	286.7 cm

METHOD OF STUDY

The samples for Foraminifera were taken continuously in the cores so that the entire length of the core was sampled. Positions of some of the samples were determined by the layering of the sediment, but where the sediment appeared to be uniform a sample approximately 5 cm. long was taken. This detailed sampling gives an accurate check on any slight vertical faunal variations which may be present. The positions of the samples in the cores are shown in Table 1.

The Foraminifera in some of the large samples were floated with carbon tetrachloride. Most samples, however, were examined without flotation to prevent the loss of specimens which are not freed by flotation.

The quantitative system of examination and study of the Foraminifera used on these cores follows that described by Phleger (1942, p. 1078). The percentage calculations are based on a 200-per cent system in which the total pelagic specimens equal 100 per cent in each sample, and the benthonic specimens equal 100 per cent. This makes it possible to consider the pelagic and benthonic groups separately, and it does not interfere with studying the total sample. In counting for species frequency only a small percentage of large samples was counted; however, the total number of specimens in each sample was either counted or estimated, and these data are listed in Table 2.

A size study of the species has been attempted. Each species was arbitrarily divided into five size groups into which the specimens appeared to group themselves. Since sizes of different species vary, size groups must be set up for each species. There are large variations in absolute size between the species in this fauna. *Globoro-*

TABLE 1.—*Positions of the samples in the cores*

Core 7–41		Core 9–41	
Sample	Centimeters	Sample	Centimeters
1	0 – 3	1	0 – 5
2	3 – 10	2	5 – 10
3	10 – 16	3	10 – 15
4	16 – 23	4	15 – 20
5	23 – 30	5	20 – 25
6	30 – 35	6	25 – 30
7	35 – 41	7	30 – 35
8	41 – 45	8	35 – 40
9	45 – 50	9	40 – 45
10	50 – 55	10	45 – 50
11	55 – 60	11	50 – 55
12	60 – 65	12	55 – 60
13	65 – 70	13	60 – 65
14	70 – 75	14	65 – 70
15	75 – 80	15	70 – 75
16	80 – 85	16	75 –80
17	85 – 90	17	80 – 85
18	90 – 95	18	85 – 90
19	95 –100	19	90 – 95
20	100 –105	20	95 –100
21	105 –110	21	100 –105
22	110 –115	22	105 –110
23	115 –120	23	110 –115
24	120 –124	24	115 –120
25	124 –128	25	120 –124.5
26	128 –131	26	124.5–128.5
27	131 –134.5	27	128.5–139
28	134.5–136.5	28	139 –145
29	136.5–140.5	29	145 –150
30	140.5–144	30	150 –155
31	144 –146	31	155 –160
32	146 –150	32	160 –165
33	150 –155	33	165 –170
34	155 –157	34	170 –175
35	157 –159.5	35	175 –180
36	159.5–161.5	36	180 –185
37	161.5–163.5	37	185 –190
38	163.5–164.5	38	190 –195
39	164.5–166	39	195 –200
40	166 –171.5	40	200 –205
41	171.5–174	41	205 –210
42	174 –180	42	210 –215
43	180 –186.5	43	215 –220
		44	220 –225
		45	225 –230
		46	230 –235
		47	235 –240
		48	240 –245
		49	245 –250
		50	250 –255
		51	255 –260
		52	260 –265
		53	265 –270
		54	270 –275
		55	275 –278

TABLE 2.—*Approximate number of specimens per sample*

Core 7–41		Core 9–41	
Sample	Number of specimens	Sample	Number of specimens
1	8250	1	3690
2	2940	2	13780
3	404	3	23100
4	1970	4	23600
5	3080	5	
6	700	6	3140
7	428	7	10240
8	494	8	13000
9	576	9	4700
10	664	10	12350
11	1150	11	9500
12	704	12	5300
13	2320	13	1820
14	958	14	26
15	274	15	126
16	171	16	5
17	410	17	64
18	264	18	216
19	154	19	324
20	212	20	453
21	350	21	474
22	437	22	727
23	343	23	834
24	221	24	205
25		25	1240
26	26	26	
27	26	27	193
28	19	28	776
29	88	29	283
30	62	30	231
31	19	31	204
32	95	32	433
33	52	33	161
34	16	34	430
35	15	35	516
36	28	36	394
37	38	37	99
38	30	38	594
39	24	39	85
40	258	40	258
41	180	41	640
42	106	42	1600
43	290	43	1080
		44	5120
		45	8230
		46	1050
		47	612
		48	1380
		49	2720
		50	2810
		51	886
		52	3
		53	0
		54	3
		55	0

TABLE 3.—*Sizes of species*
(In millimeters)

Species	Size groups				
	I	II	III	IV	V
Globigerina bulloides	.30	.50	—	—	—
G. inflata	.45	.65	.75	1.00	1.20
G. pachyderma	.25	.35	.50	—	—
G. dubia	.55	.65	.85	1.05	1.25
Globigerinoides rubra	.50	.60	.75	.85	
Globoratalia menardii	1.15	1.30	1.50	1.60	1.90
Uvigerina peregrina	1.10	1.35	1.90		
Elphidium incertum	.30	.50	—	—	—
Cibicides sp. 1	.30	.50	.70	—	—
Virgulina sp. 1	.55	.75	.85	—	—

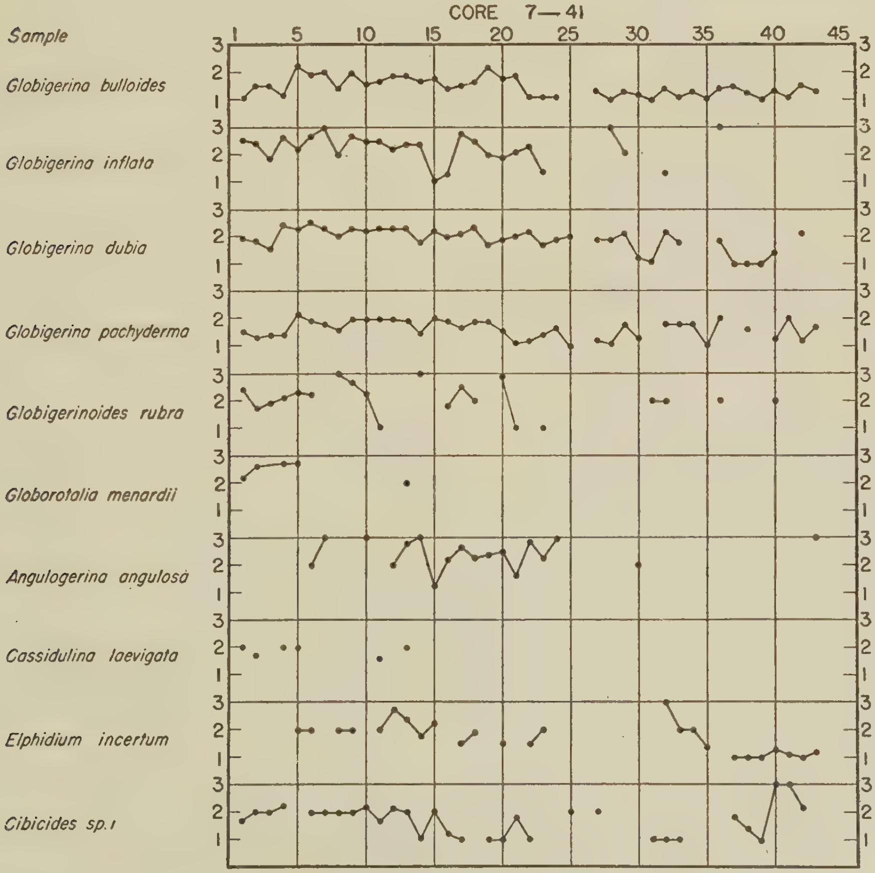

FIGURE 1.—*Mean size groups of species in Core 7-41*

talia menardii, for example, in its smallest size group (Group I) is larger than the largest size group of either *Globigerina inflata* or *Globigerinoides rubra*.

The size in millimeters for each of the size groups identified for 10 of the most important species in the cores is given in Table 3. The sizes and size groups have been set up on an arbitrary basis utilizing past experience in approximate sizes of species likely to occur, and a reference slide of sizes was made up for each species.

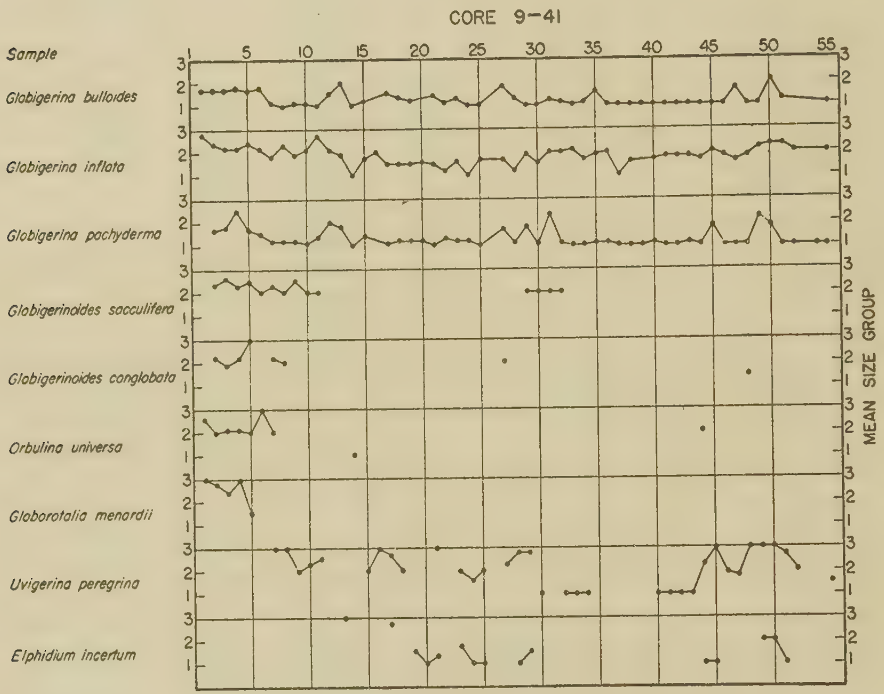

FIGURE 2.—*Mean size groups of species in Core 9-41*

Thus in some species (*see* Table 3) only two or three of the five sizes are given since larger or smaller sizes were expected in the cores but were not found. Theoretically the sizes should grade evenly from the smallest ever encountered, in Size Group I to the largest ever found, in Size Group V. The size-group system here used may not be adequate for other areas, but it is the most practicable the writers could devise. The mean size group for the various species in each sample is listed in Figures 1 and 2. This is only an approximation of the actual mean size and is roughly comparable to the median diameter determined by sifting sediments with a series of graded sieves. The smaller size groups appear to represent juvenile specimens in the globigerinids, and possibly in the other species.

THE FORAMINIFERA

GENERAL STATEMENT

Species listed in Plate 1 are the most common and important ones in the samples studied. Conclusions concerning water temperature during the length of time represented by the cores can be made mainly from the percentage-occurrence data listed in Plate 1. Some of the rare species were not used because they are difficult to identify and are of little quantitative significance, but these constitute less than 1 per cent of the specimens in any sample. Only species which could be given consistent identifications have been used as important indicators of environmental conditions. Most of the species in the present faunas are illustrated by Phleger (1939, Pls. 1–3).

DISTRIBUTION OF CERTAIN FORAMINIFERA

Certain faunas of Foraminifera are limited in distribution at the present time to either tropical, subtropical, temperate, sub-Arctic, or Arctic waters. When occurrences of faunas like those at present living in regions limited by certain temperatures are found below the surface sediments, these older faunas are considered to be of the same temperature range as their modern counterparts. The great majority of the samples were composed almost entirely of pelagic types; the top samples from the cores are essentially a *Globigerina* ooze.

Present distribution of certain species important in this study which have been recorded previously by other investigators is partially listed below. Phleger and others have referred to distribution of certain species in general terms; this present list constitutes somewhat more specific regional, and therefore temperature, distribution of the species.

Identification of *Globigerina bulloides* varies so widely that distribution records may contain several related species; universal distribution, however, is possible. Herron-Allen and Earland (1932) report common to abundant occurrences of *G. bulloides* from the South Atlantic in the Falkland Island area and that of the adjacent seas. Earland (1934) adds that most of these occurrences were outside the Antarctic convergence line, and thus largely excluded from the coldest waters of the Antarctic. Schott (1935) records *G. bulloides* from the equatorial water of the Atlantic but points out that the occurrences are most common in the relatively cool New Guinea Current. *G. bulloides* appears to be an indicator of relatively cool water but not necessarily of Arctic water. Occurrences in tropical or even subtropical water should be checked with cold-current charts. Lack of consistent identification on the part of several workers and paucity of accurate frequency-distribution data prevent this at the present time.

Globigerina dubia is recorded by Cushman as abundant in samples from the western North Atlantic. Some of the specimens in the present samples which were identified as *G. dubia* may belong to *G. bulloides*. *G. dubia* appears to be of dominantly warm-temperate distribution, but this is not certain.

Globigerina inflata is reported by Phleger (1939) as common to abundant in the modern warm-temperate waters of the western North Atlantic Ocean. Herron-Allen and Earland (1932) record *G. inflata* as abundant in the Falkland Island area and as being the most common pelagic species in this area. This area has a surface-temperature range from 4° to 8°C. (Sverdrup, 1942). Chapman and Parr (1937) report this as a common species in the cool waters south of Australia, and Earland (1933; 1934) finds it common in the South Georgia region and elsewhere on the edge of the Antarctic Ocean. From these occurrences *G. inflata* seems to be a warm-temperate to cool-temperate type. Its distribution appears most common in areas having an intermediate temperature. The present writers interpret *G. inflata* as primarily warm-temperate in distribution.

Chapman and Parr (1937) report that *Globigerina pachyderma* is very common in the Antarctic Ocean south of Australia. This is corroborated by reports of Herron-Allen and Earland (1932) and Earland (1933; 1934) who indicate that it is universally distributed in the Falkland Island area and that it is the most abundant globigerinid in the Antarctic. *G. pachyderma* appears to be largely Arctic (or Antarctic) to sub-Arctic in range and should indicate cold water if it occurs with a high frequency to the exclusion of most other pelagic types. The present writers find it difficult to explain the rather high percentage of *G. pachyderma* in many of our warm-water samples. There are two possible explanations: Either (1) identification of this species has not been consistent, or (2) there is a mixture of cold- and warm-water pelagic types in this region on the northern margin of the Gulf Stream.

Globigerinoides conglobata is widely distributed in the tropical waters around the Philippine Islands (Cushman, 1921). It is extremely abundant in the warm-temperate regions of the Atlantic according to Cushman (1920–1931), and Phleger (1939) reports it as common to abundant in many warm-temperate samples from the western North Atlantic. Earland (1933) reports two occurrences in the Antarctic near South Georgia, and these seem to be the only occurrences of this species known in the Antarctic. *G. conglobata* is tropical to warm temperate in distribution.

Globigerina rubra is recorded by Cushman (1920–1931) as abundant in the warm-temperate waters of the western North Atlantic. Cushman (1921) reports rare occurrences of this species in the tropical waters of the Pacific region. Herron-Allen and Earland (1932) and Earland (1933) report a few occurrences in the Antarctic. This species was the most abundant found in the plankton tows taken near the outer edge of the Gulf Stream in the North Atlantic by Phleger (1945). *G. rubra* seems to be a warm-temperate species and in abundance may be particularly characteristic of Gulf Stream and Sargasso Sea water.

Globigerinoides sacculifera is recorded by Cushman (1921) as very abundant in the tropical regions of the Pacific. Phleger (1939; 1942) and Cushman (1920–1931) report it as common to abundant in the warm-temperate regions of the Atlantic. One specimen was recorded on the Australasian Antarctic Expedition (Chapman and Parr, 1937). *G. sacculifera* is a tropical to warm-temperate species.

Globorotalia menardii is reported as common in the tropical Pacific waters (Cushman, 1921). It is abundant in the warm-temperate regions of the North Atlantic (Cushman, 1920–1931; Phleger, 1939; 1942); Schott (1935) reports this species abundant in his tropical Atlantic stations. Four specimens are reported by Herron-Allen and Earland (1932) and Earland (1934) from the Antarctic. This is a tropical to subtropical species.

Cassidulina laevigata is reported by Miss Frances Parker (personal communication) as very common in the shallow coastal waters of the western North Atlantic. Cushman (1921) found it rare in the tropical waters of the Pacific. Cushman (1920) reports this species rare in the Arctic, while Herron-Allen and Earland (1932) record widespread occurrences in the Antarctic. It is probably a cool-temperate or coastal species.

Elphidium incertum is reported by Miss Parker (personal communication) and Cushman (1920–1931) as common in the western North Atlantic. Cushman (1920) reports it from the Arctic and Herron-Allen and Earland (1932) and Earland (1933; 1934) record it from the Antarctic. It is probably cool-temperate in range.

CORE FAUNAS

CORE 7-41

Samples 1–5 contain the upper warm-water fauna. *Globigerina inflata* constitutes a large percentage of the fauna, and this is the only stage in which *Globigerina menardii* shows any significant occurrence. All of the other warm-water species are present in quantity, and *Globigerina pachyderma* is of relatively low frequency.

Samples 6–15 contain the upper cold-water fauna. All of the warm-water indicators are absent except for a relatively low frequency of *Globigerina inflata* which continues throughout this stage. *Globigerina pachyderma* begins its increased frequency in sample 6 and constitutes more than 50 per cent of the pelagic group throughout this stage. Occasional occurrences of warm-water species are present in this stage but never constitute over 1 per cent of the pelagic group present in any one sample.

Samples 17–23 contain a middle fauna which is variable but is of a warmer-water aspect than the cold zone above; it indicates cooler-water conditions than is evidenced by the fauna at the top of the core. The occurrences of *Globorotalia truncatulinoides* and the sudden decrease of *Globigerina pachyderma* in sample 17 mark the upper boundary of this stage. Samples 24–29 also may be a part of this stage.

Samples 30–43 contain the lower cold-water fauna. *Globigerina inflata* occurs less frequently in this stage in the core than in any other. *Globigerina pachyderma* increases in sample 30 and remains prominent. A cool rather than cold-water stage is evident in samples 37–40 where there are two occurrences of *G. rubra* and there is a decrease in *G. pachyderma*. Sample 43 shows a marked decrease in *G. pachyderma* suggesting a warmer stage not far below the section of sediment contained in this core.

CORE 9-41

Samples 1–7 contain the upper warm-water fauna with a warm-water maximum below sample 1. The first sample contains only three definite warm indicators. *Globorotalia menardii* increases its frequency in sample 2, then drops almost steadily and is absent from sample 6. Samples 2–6 contain six warm-water species. Sample 7 shows a sharp change in the major pelagic species from *Globigerina inflata* to *G. bulloides* but still contains four warm-water species. Samples 7–11 appear to be transitional between cold and warm water.

Samples 8–26 contain the upper cold-water fauna with no clearly defined upper and lower boundaries. From sample 21 to the bottom of this stage there are minor occurrences of warm-water species, none of which counterbalance the high percentages of *G. pachyderma* and *G. bulloides*.

Samples 27–32 contain a middle warm-water fauna which may represent somewhat cooler-water conditions than the present-day fauna.

Samples 33–35 are intermediate.

Samples 36–55 contain a cool- to cold-water fauna. Infrequent occurrence of some warm-water species suggests that this stage is somewhat more temperate than the upper cold-water stage. A distinct tendency toward warm water is represented in samples 48–51 in which *Globigerina pachyderma* shows a decrease in frequency and in which three warm-water species show more occurrences and higher frequencies than in the zone above. The samples below sample 51 indicate continued cool to cold water, and this fauna continues to the bottom of the core.

SIZE DISTRIBUTION

The size group means represent that point at which 50 per cent of the specimens in a species belong to a larger size group and 50 per cent belong to a smaller size group. A discussion of the apparent trends of mean sizes for a few of the most indicative species is here related to the water-temperature interpretations.

Globigerina pachyderma is a cold-water species which occurs throughout most of the samples of the cores 7-41 and 9-41 but with varying frequency. The size means in these two cores show opposite trends. In core 7-41 *G. pachyderma* generally appears to remain below size mean 1.5 in warm stages and varies from 1.5 to 3.0 in cold stages. In core 9-41 it remains mostly above 1.5 in the warm-water stages and below 1.5 in the cold-water stages. This suggests that a change in size occurs in *G. pachyderma* at the same time as this species changes in frequency, but the direction of change is inconsistent and cannot be explained at present.

Globigerina bulloides indicates the same change as the above species; it generally changes from below 1.5 in the warm-water stages to above 1.5 in the cold-water stages of core 7-41 and above 1.5 in the warm-water stages to below 1.5 in the cold-water stages in core 9-41. This indicates that a change in mean size accompanies a change in frequency, but no absolute correlation with the temperature is possible.

Globorotalia menardii, a very warm-water type, shows marked decrease in size mean as its frequency drops when approaching a cold-water stage, especially in core 9-41. *G. menardii* increases in size as the water becomes warmer.

Generally, the warm-water species appear to change their mean sizes in response to a change in water temperature.

DISCUSSION

GENERAL STATEMENT

Interpretation of the Foraminifera in submarine cores is mainly a problem in ecology. Most of the species and over 90 per cent of the specimens in these samples are pelagic, and these Foraminifera are presumed to inhabit the upper layers of oceanic water. Pelagic species do not necessarily float awash but live somewhere above the bottom. They live mainly in the top 100 meters according to data collected in the South Atlantic by Schott (1935). Only living species collected from plankton tows can be considered definitely pelagic in habitat; a list of known pelagic Foraminifera is given by Cushman (1940).

Although it usually is assumed that the pelagic assemblage in bottom sediments indicates conditions in the upper layers of water, this is not necessarily true. Phleger (1945) collected larger populations of living pelagic Foraminifera at 800 to 1000 meters than at 100 meters at two localities in the western North Atlantic, but these data need further verification. (*See* Phleger, 1942, p. 1094–96.)

INTERPRETATION OF CORE FAUNAS

Temperature changes.—Four water-temperature stages are suggested by the faunas in the cores. (*See* Figure 3.) From top to bottom of the cores they are as follows: (1) the present warm-temperature water stage with a warm maximum in core 9-41 a short distance below its top; (2) a cold-water stage; (3) a warm-temperate water stage; (4) a cold-water stage extending to the bottom with a possible cool-temperate water indicated just above the bottom of the cores.

Cushman and Henbest (1940, Figs. 11–21) found two or more Arctic or sub-Arctic faunas, separated by warm-water faunas, below the tops of the cores taken from the North Atlantic at North Latitude 36° to 49.5°. Phleger (1939, Figs. 2–4; 1942, Pl. 3) indicates at least one cold-water fauna beneath the modern fauna, represented by changes in the pelagic and benthonic assemblages, in cores from the continental slope of the western North Atlantic. The two warm-water and the two cold-water stages described in cores 7-41 and 9-41 appear to be comparable to the upper stages identified in these other North Atlantic cores.

The upper warm-water fauna appears to have a maximum development below the top in core 9-41. Deevey (1939, Table 1) has found evidence, in pollen analysis of Connecticut lake sediments, of a postglacial optimum about midway between the last deglaciation and the conditions now obtaining in the region. Deevey correlates this optimum with evidence collected by Auer in Eastern Canada, McCulloch in New York, Sears in Ohio, and Voss in Wisconsin. Phleger (1939, p. 1416) has found a post-Wisconsin foraminiferal fauna indicating warmer surface-water conditions than now obtained. He correlated this with the postglacial optimum suggested by the pollen-analysis studies. Possibly the upper "warmer-than-present" assemblage in core 9-41 is an oceanic evidence of the postglacial optimum recognized on the nearby land.

Ray (1940, p. 1912–13) has identified five Wisconsin substages in the southern Rocky Mountains, each separated by a warmer interim. Substages of the Wisconsin have been identified in northern Europe which may be correlatives of the Rocky Mountain stages (Ray, 1940, p. 1914). It is suggested that the warm- and cold-water faunas identified in Atlantic cores by Cushman and Henbest (1940) and Phleger (1939; 1942) and faunas apparent in the present cores may be correlated with the subdivisions of Wisconsin time rather than with other major glacial stages of the Pleistocene.

Climatic changes would be reflected in the temperature of adjacent oceanic water, and in the western part of the North Atlantic changes in the course of the Gulf Stream probably would be associated with climatic changes.

These cores were obtained from an area near the edge of the Gulf stream, which

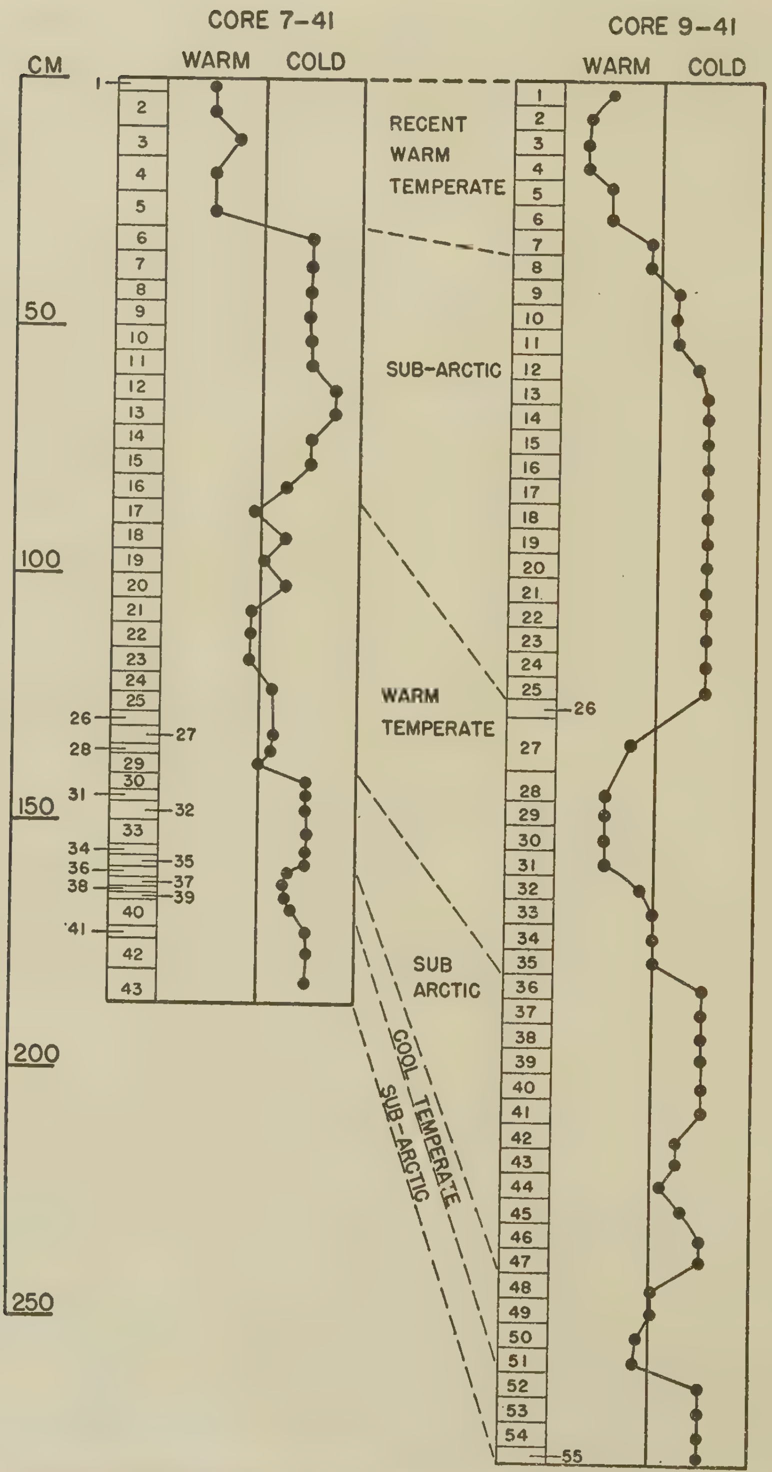

FIGURE 3.—*Approximate relative water temperatures indicated by the foraminiferal faunas in the cores*

suggests that minor changes in water temperature, indicated by faunal variations, may be due to shift in the position of Gulf Stream water masses not necessarily associated with prolonged climatic changes. Small faunal variations might be due to the movements of counter currents and eddies into areas of lower or higher water temperature. According to Iselin (1936) the northeasterly portion of the Gulf Stream, the North Atlantic Current, contains many such counter currents, eddies, and bodies of dead water whose temperatures differ from that of the main current. From this approximate area, Cushman (1920–1931) records occasional occurrence of species foreign to the apparently normal fauna.

Cushman and Henbest (1940, p. 47) suggest rafting of specimens by seaweed and ice into areas foreign to their normal environment. These methods account for unusual occurrences of a few specimens, but they are not the only possible explanations for samples which are radically different from those above or below them, at least not in the area covered by these cores under the present ecologic conditions. Comparatively sudden shift of a mass of warm water into an area previously foreign to it would cause a deposition of pelagic species characteristic of the water. It might also upset the ecology of the entire water column. If the temperature-range tolerance of some species is as limited as records of distribution suggest, then the sediments deposited in such an area would contain: (1) an abundance of the fauna living in the area immediately before the change occurred; (2) abundance of species living in the warm mass of water which moved into the area. The result may then be the deposition of a sample resembling a transitional fauna. If considerable cooling of the entire water mass eventually occurs, causing high mortality, the number of specimens deposited during such a short stage would represent a shorter period of time than the same number of specimens accumulated under stable conditions.

SIZE TRENDS

Pelagic species.—The results of the study of size trends are not conclusive and raise more problems than they solve. There appears to be some indirect relationship between the size mean of some species and water temperature. A change in mean size often occurs coincident with the faunal changes presumed to be due to temperature changes. Thickness of test has not been studied in detail, although warm-water samples appear to have thicker tests than those in cold-water samples.

Changes in mean size within the cores may be either abrupt or distributed through a transitional layer. The same species have not changed in relation to water temperature in the same manner in all cases in these cores, and this makes interpretation difficult. Some species do not enter a fauna with a large mean size but attain a mean of 1.5 or larger size group only after having become firmly established as an addition to the fauna. This appears to accompany a reduction in mean size of one or more other species. The appearance of a species not previously present in a locality may cause withdrawal or decrease in frequency of occurrence of certain other species. Thus no sample was found to contain an equally high frequency of both *Globigerina bulloides* and *G. inflata*, and the mean size of the one in greater abundance in a sample is usually larger than the size mean of the other. In general, the mean size of a species appears to be greatest when the frequency of occurrence of the species is high and the water temperature (ecologic conditions) apparently has attained an optimum for the species. A smaller mean size is common for species of low frequency of occurrence.

A summary of possible causes of size limitation might be: (1) water temperature; (2) genetic constitution; (3) size averages determined by casualties of juvenile forms caused by some ecologic factors such as temperature or change in food supply. Mechanical sorting of the sizes comparable to the sorting of sediments by currents also is a possibility.

Benthonic species.—The benthonic group is masked by the quantity of pelagic specimens in these cores. (*See* Cushman and Henbest, 1940, p. 48, for a similar condition in other cores.) The number of benthonic specimens in the present samples is insufficient for any relationships between size and known factors of distribution to be of any value. The benthonic forms in this area generally tend to have larger mean sizes than the pelagic forms. *Uvigerina peregrina* is an outstanding example of large size, while *Elphidium incertum*, particularly in core 9-41, is generally quite small.

FUTURE WORK

Study of these two cores has demonstrated the usefulness of the continuous method of sampling for Foraminifera since minor variations in ecologic conditions are more readily indicated than in widely spaced samples. Additional cores should be obtained and studied by the continuous sample method on a quantitative basis to obtain an accurate picture of vertical faunal variations and their implications. The study of sizes is so suggestive that it should be explored further. The present paper indicates only one method of investigation.

More adequate information on the ecology of Foraminifera is absolutely essential. Quantitative collection of living pelagic Foraminifera from various water depths and various environments will supply data on relationships to temperature and to the remainder of the plankton. These collections should be seasonal. Experimental work on life cycles and on temperature relationships should be an aid in these problems but will be difficult of execution.

CONCLUSIONS

(1) Two cores from the basin of the North Atlantic contain two sub-Arctic faunas separated by a warm-temperature fauna. The sub-Arctic faunas are interpreted as representing the two latest stages of the Wisconsin.

(2) A post-Wisconsin fauna in core 9-41 indicating warmer surface waters than obtain at present apparently is correlated with the postglacial "optimum."

(3) Continuous sampling of the cores has revealed minor faunal variations which may be due to intermixing of water masses of different temperatures.

(4) Studies of size groups suggest a possible relationship between mean size and water-temperature conditions in some species.

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ACTION OF ANTIFOULING PAINTS

II. Solubilities of Antifouling Toxics in Sea Water

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The solubilities in sea water of various copper and mercury compounds which have been proposed as antifouling toxics cover a very wide range, from 10^{-3} to over 10^5 micrograms of metal per cc. Cuprous oxide, the toxic which has been most widely used, has a solubility of 5.4 micrograms of copper per cc., high enough to be effective but not so high that its leaching rate from antifouling paints is too difficult to control.

THE most commonly used antifouling toxics are compounds of copper and mercury. Salts of the latter metal were employed very early in the development of antifouling coatings; the use of mercuric oxide was patented in 1857 (*14*), mercuric chloride in 1864 (*3*), and mercurous chloride in 1885 (*4*). The use of cuprous oxide was described in 1863 (*13*), and this substance has found wide application in antifouling paints ever since. In many early formulations "copper oxide" was specified without distinguishing between the cuprous and the cupric compound.

The solubility and rate of solution of cuprous oxide in sea water were reported in the first paper of this series (*5*). Although no other toxic substance has been studied in such detail, it is possible to summarize here data on the sea water solubilities of a number of these compounds. Some of the data are based on experimental measurements and some on calculations from thermodynamic data in the literature.

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COPPER COMPOUNDS

Experimental measurements of the solubilities of copper compounds in sea water were carried out at 25° C. After equilibration, the filtered solutions were analyzed for copper by the method of Coulson (*2*, *8*), and pH measurements were taken with a Beckman glass electrode.

Cuprous Oxide. The solubility of cuprous oxide in air-free sea water was shown (*5*) to be proportional to the hydrogen ion concentration and unaffected by carbonate ions. In normal sea water at pH 8.1, the solubility is 8.6×10^{-5} moles copper per liter, or 5.4 micrograms per cc. The measured values are in good agreement with those calculated (*5*) from thermodynamic data obtained with simple chloride solutions, and on this basis it is concluded that the cuprous copper exists in sea water solution largely as the complex ions $CuCl_2^-$ and $CuCl_3^{--}$.

Table I. Analyses of End Products of Reaction between Sea Water and Copper and Cuprous Oxide

Source	Cu, %	CO_2, %	Cl, %	Investigators
Copper	67	11	4	Sexton (*11*)
Copper	50–55	7–12	3–6	Bengough & May (*1*)
Copper	51–58	11	3	Authors
Cuprous oxide	51	...	2	Authors

Table II. Solubilities of Copper and Mercury Compounds in Sea Water at pH 8.1

Compound	Soly., µg./cc.	Source
Cupric citrate	>170,000	Exptl.
Cuprous chloride[a]	3,100	Calcd.
Cuprous oxide[a]	5.4	Exptl.
"Basic cupric carbonate"	0.5	Exptl.
Aged "b.c.c."[b]	<0.1	Exptl.
Cupric hydroxide	0.013	Calcd.
Cupric oxide	0.001	Calcd.
Mercuric chloride	200,000	Exptl.
Mercuric oxide	80,000	Calcd.
Mercurous chloride	0.3	Calcd.

[a] In oxygen-free sea water.
[b] "Basic cupric carbonate" aged in sea water for one year.

In the presence of air, cuprous copper dissolved from cuprous oxide in sea water is oxidized to the cupric form, and is partially reprecipitated as a mixture of basic cupric carbonate and oxychloride.

Cuprous Chloride. From the same thermodynamic data used to calculate the solubility of cuprous oxide (*5*), the solubility of cuprous chloride in air-free sea water is computed to be 5.1×10^{-2} *M*. While there are no experimental measurements, this value may be taken with some confidence in view of the agreement between measured and calculated solubilities of cuprous oxide. As in the case of cuprous oxide, copper dissolved from cuprous chloride in sea water in the presence of air is oxidized and partly reprecipitated.

Cupric Oxide and Hydroxide. In contrast to cuprous oxide, cupric oxide has been found to have a negligible solubility in sea water within the limits of the analytical method employed

($<10^{-6}$ *M*). The value calculated from thermodynamic data in the literature is very small. Latimer (*9*) gives the ion product $(Cu^{++})(OH^{-})^2$, in equilibrium with cupric hydroxide, as 5.6×10^{-20}; at pH 8.1, if the activity coefficient of cupric ion in sea water (ionic strength 0.63) is taken as 0.17, the corresponding copper concentration is 2.1×10^{-7} *M*. Using Latimer's value (*9*) of 1590 calories for the free energy of hydration of cupric oxide to hydroxide, the corresponding solubility of cupric oxide is calculated to be 1.4×10^{-8} *M*.

Basic Cupric Carbonate. Although basic cupric carbonate has not been widely suggested as an antifouling toxic, it is of interest in this connection because of its formation in the reaction of sea water with either cuprous oxide or metallic copper in the presence of air. When the supply of oxygen is ample, the end product of either reaction is a bluish precipitate whose composition, according to Bengough and May (*1*), corresponds to a mixture of basic cupric carbonate and oxychloride, in which the former predominates. The results of analyses of such precipitates derived from copper, by these authors (*1*) and also by Sexton (*11*), are compared in Table I with our analyses of precipitates from copper and cuprous oxide. The data show considerable variation, but the results of the different investigators are in fair agreement. The average chlorine content of 3% corresponds to a content of about 20% of atacamite, $Cu_4(OH)_6Cl_2 \cdot H_2O$, a salt which was identified by Rooksby and Chirnside (*10*) in the corrosion products of copper.

Just as the composition of this precipitate shows variations, so also does its solubility in sea water. A large number of experimental determinations has given values lying between 5 and 10×10^{-6} mole of copper per liter. These solutions would appear to be supersaturated with respect to cupric hydroxide.

A sample of basic cupric carbonate precipitate which had aged for one year under sea water was found to have a negligible solubility by the analytical method employed ($<10^{-6}$ *M*). The chloride content of this material was 14% as compared with 16% for pure atacamite, which suggested that conversion of carbonate to oxychloride had occurred during aging.

Cupric Citrate. This substance is of interest in experimental studies of antifouling action because its solubility in sea water is enormously greater than those of the other copper compounds discussed here. By mixing 1 mole each of cupric carbonate and citric acid with 1.6 moles of sodium hydroxide in aqueous solution and precipitating the reaction product with ethanol, a dark blue crystalline salt is obtained whose copper content corresponds to the formula $NaCuC_6H_5O_7$. This material is hygroscopic and has an enormous solubility in sea water; solutions of concentrations as high as 2.7 *M* have been prepared. Evidently a very stable complex ion is formed which prevents the precipitation of the copper as basic carbonate.

MERCURY COMPOUNDS

Experimental measurements of the solubilities of mercury compounds in sea water were carried out by equilibrating at 25° C.

and analyzing the filtered solutions by titration with dithizone in chloroform (*15*).

Mercurous Chloride. This compound is decomposed in the presence of other chlorides and, therefore, presumably in sea water, with the formation of mercuric chloride and metallic mercury. The equilibrium constant for the reaction, $Hg + Hg^{++} = Hg_2^{++}$, is given by Latimer (*9*) as 81, and the solubility product of Hg_2Cl_2 as 1.1×10^{-18}. The dissociation constant of the weak salt $HgCl_2$ is given by Sherrill (*12*) as 10^{-14}. From these data and the concentration of chloride ion in sea water (0.48 *M*), neglecting activity coefficients, the concentration of dissolved mercuric mercury in sea water in equilibrium with mercurous chloride and metallic mercury is calculated to be 1.4×10^{-6} *M*. The amounts dissolved as determined experimentally are of this order of magnitude, but depend upon the amount of solid phase present in a complicated manner which requires further study.

Mercuric Oxide. The solubility of mercuric oxide has been measured only at a pH considerably alkaline to that of normal sea water. At pH 9.7 it is about 2×10^{-3} *M*. The solubility at pH 8.1 calculated from the ionic product as given by Latimer (*9*), 2.7×10^{-26}, and the dissociation constant of $HgCl_2$, quoted in the preceding paragraph, neglecting activity coefficients, is 0.39 *M*.

Mercuric Chloride. The solubility of mercuric chloride in sea water has been found experimentally to be approximately 1.0 *M*.

DISCUSSION

The solubility data, summarized in Table II, give the values in micrograms of metal per cc. of sea water. A wide range of solubilities is represented by the compounds listed.

The extremely low solubilities of such compounds as cupric oxide and hydroxide suggest a priori that these substances can never function effectively as antifouling toxics. The very high solubilities of cupric citrate and mercuric chloride, on the other hand, suggest that it might not be easy to utilize such compounds in antifouling paints because of the difficulty of controlling the leaching rate to prevent premature exhaustion of toxic.

The solubility of cuprous oxide is intermediate in the range covered by Table II, although it is quite low compared with those of inorganic salts in general. As stated in the preceding paper (*5*), this moderately low solubility facilitates control of the leaching rate from a paint in which it is compounded.

The leaching rate of toxic from a paint, which determines the antifouling effectiveness, depends upon many factors in addition to the solubility of the toxic. The proportion of toxic in the paint formulation, and the composition of the matrix, both influence the leaching rate profoundly, as Tables V, VI, and VII of an earlier article (*8*) indicated. These variables will be discussed in the succeeding papers of this series (*6*, *7*).

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ACTION OF ANTIFOULING PAINTS

III. Maintenance of the Leaching Rate of Antifouling Paints Formulated with Insoluble, Impermeable Matrices

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Maintenance of the leaching rate by an antifouling paint which contains a high loading of toxic in an insoluble, impermeable matrix depends upon continuous contact of toxic particles throughout the paint film. When paints formulated with cuprous oxide and Vinylite are extracted either in citrated sea water in the laboratory or in the open sea, the toxic dissolves and leaves the matrix intact. The rate at which the leaching rate falls during extraction, as well as the total amount of toxic extractable, is sensitive to the proportion of toxic in the paint. This proportion must exceed 30% by volume to make particles below the surface accessible to solvent action. Antifouling coatings of this type have the advantage of being effective when applied as a thin film, with good resistance to erosion.

AN EFFECTIVE antifouling paint must release toxic continuously over a prolonged period. Selection of a toxic with a moderately low solubility, as described in the first two papers of this series (*1*, *2*), can facilitate attainment of this result. However, the paint must be formulated to provide a mechanism for the eventual dissolution of toxic particles which are originally buried deep below the surface.

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One possible mechanism for the prolonged leaching of toxic from the interior of a paint is based on the use of a matrix which is sufficiently permeable so that water can enter the paint film and dissolve the toxic, and the toxic ions can subsequently diffuse to the surface and be released there. Experiments with certain matrices which possess substantial permeabilities to water vapor have been described by Young and Schneider (*5*). Successful paints can also be made with binders which have very low permeability to water and ions and are insoluble and inerodible. The mechanism of prolonged leaching in such paints, which require a high loading of the toxic pigment to be effective, is discussed in the present paper. Still another mechanism, which permits paints to be formulated with considerably lower toxic loadings, will be described in a later paper of this series (*3*).

PAINTS WITH HIGH TOXIC LOADING

The leaching behavior of paints with very high loadings of toxic can be explained on the basis of continuous contact of toxic particles throughout the paint structure so that, as soon as one particle is dissolved, another beneath it is exposed to solvent action. These have been colloquially termed "cannon ball" paints, since the particles are pictured as arranged roughly like the familiar structure of a pile of cannon balls, with the binder filling the interstices.

The high loading of toxic which is required to provide continuous contact demands a strong, tough binder to ensure that the paint film will retain its integrity and has adequate resistance to erosion. The use of Vinylite and other vinyl polymers as binders for antifouling toxics was introduced by the Bakelite Corporation, working under contract with the Office of Scientific Research and Development, and has made possible the preparation of paints with very high loadings and excellent mechanical properties.

The properties of a series of antifouling paints with high loadings of cuprous oxide are described here. Evidence is presented that such paints maintain their toxic leaching rates over long periods of time by virtue of continuous contact of the toxic particles.

MATERIALS AND METHODS

The paints used in these experiments were compounded with materials kindly supplied by the Bakelite Corporation—namely, cuprous oxide (electrolytic), polyvinyl chloride-acetate (Vinylite VYHH), and rosin, the resins being dissolved in methyl ethyl ketone. In a series of nineteen different paints the proportion of Vinylite in the matrix varied from 25 to 100%, and the proportion of cuprous oxide varied from 60 to 90% of the total solids.

Panels of ground glass, 3 × 4 inches, were weighed, coated on both sides, allowed to dry, and reweighed. Their initial leaching rates in sea water were determined by the standardized techniques described in a previous paper (*4*). Later they were submitted to various treatments, to be described, and their leaching rates were again measured. In certain cases an analysis of the panel was made at the end of the experiment. It was washed with distilled water, dried, and reweighed. Then, to determine the amount of cuprous oxide remaining, the paint was removed from the glass with hot sulfuric and nitric acids and digested to oxidize the organic matter, and the copper was titrated with thiosulfate.

SURFACE-EXPOSED TOXIC

A surface freshly coated with antifouling paint may be considered to be covered with irregularities where the particles of toxic project from the solidified matrix, as shown schematically in Figure 1.

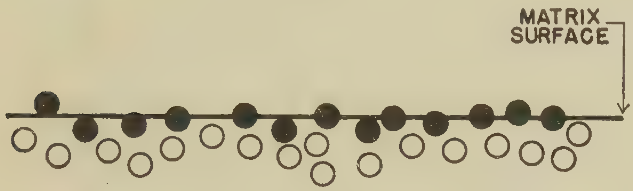

Figure 1. Schematic Cross Section of the Surface of a Fresh Coat of Antifouling Paint

Since paint vehicles wet the pigments suspended in them, it might be expected that each projecting toxic particle would be covered by a very thin layer of matrix. Actually most antifouling paints containing cuprous oxide begin to release copper immediately (or within a few minutes) after immersion in sea water. Therefore, any such matrix skin must ordinarily be too thin to interfere with dissolution of toxic and is, presumably, quickly removed after immersion. (In certain coatings applied as hot melts, there is some evidence of an initial surface coating which interferes with leaching and persists several days after immersion in sea water.)

The initial leaching rate of a fresh surface, such as Figure 1 illustrates, is the product of the specific rate of solution of the toxic and the total area of toxic particles exposed (represented by black circles). The specific rate of solution of cuprous oxide and its dependence on temperature, hydrogen and chloride ion concentrations, and ionic strength have already been discussed (*1*). In laboratory measurements of the leaching rate, the latter quantities are all kept constant. The leaching rate is, therefore, a measure of the area of toxic exposed on the surface (per unit panel area) at the time the measurement is made. The mass of surface-exposed toxic may also be determined by complete extraction of the surface under certain conditions.

EXTRACTION. When no mechanism is afforded to make the toxic particles beneath the matrix surface (open circles of Figure 1) accessible to solvent action, the total amount of extractable toxic is represented by that in the surface layer. Experiments were performed to show how the leaching rate changes when such a surface layer is gradually depleted by extraction in different ways.

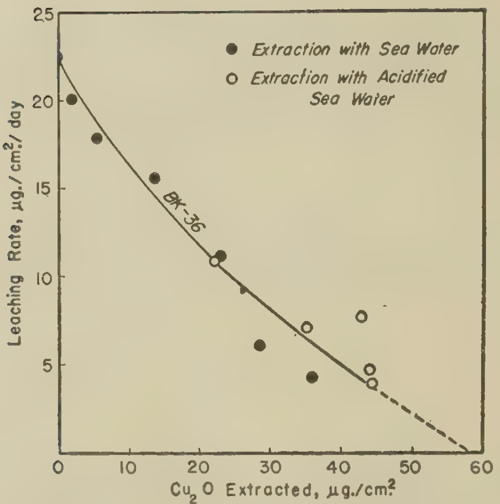

Figure 2. Extraction of Surface-Exposed Toxic from an Antifouling Paint Containing 40% Cuprous Oxide in a Hard Matrix

Panels were coated with a paint whose dry composition was 40% cuprous oxide, 30% Vinylite, and 30% rosin. This mixture of resins is insoluble in sea water, and the volume fraction of toxic is so low (0.12) that isolation of the surface-exposed particles from one another and from underlying particles is assured. The leaching rates were measured, and the surface-exposed toxic was exhausted in two ways: (*a*) by leaching in six successive changes of sea water for 4-hour periods, the average leaching rate being calculated for each period; and (*b*) by extraction in sea water

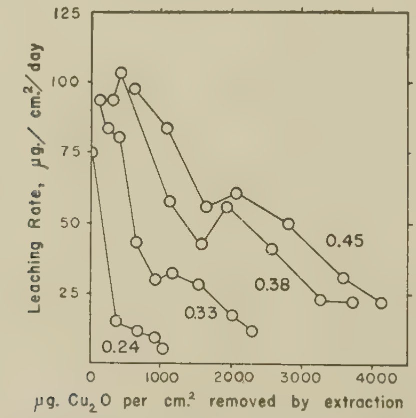

Figure 3. Changes in Leaching Rates of Heavily Loaded Cuprous Oxide Paints during Extraction in Citrated Sea Water

Figures on curves refer to volume fractions of toxic in paints.

(containing 0.06% citric acid, adjusted with sodium hydroxide to pH 3.9) for various periods, followed always by a leaching rate measurement in plain sea water. The amount of cuprous oxide removed from the surface was calculated from integration of the leaching rate-time curve or from analysis of the citrated solutions.

The leaching rate is plotted against the total amount of cuprous oxide removed in Figure 2. It falls steadily as extraction proceeds; the results in sea water and in acidified sea water are in reasonably good agreement. By extrapolation, the leaching rate approaches zero when 57 micrograms of cuprous oxide per sq. cm. of surface have been extracted. It may be concluded that, for this paint, the total mass of cuprous oxide particles originally exposed (black circles in Figure 1) was 57 micrograms per sq. cm.

The ratio of mass of toxic initially exposed to initial leaching rate gives a rough estimate of the leaching life of a single layer of cuprous oxide particles[2]. In this case it was 57/22 or 2.6 days. The surface was, in fact, virtually exhausted of toxic after 24 hours in sea water. It is clear that, if a paint is compounded of toxic particles of this type, many layers of particles will be necessary for the maintenance of leaching over a long period of time, and that dissolution of toxic must eventually take place from deep within the interior of the paint. The problem is, then, to make the particles buried deep in the paint accessible to solvent action. The following data show how the desired result may be obtained by increasing the toxic loading.

EXTRACTION OF CUPROUS OXIDE FROM HEAVILY LOADED PAINTS

Paints which contain higher loadings of toxic continue to leach after the surface layer of toxic has been dissolved. In order to study the behavior of such paints, a series of mixtures was prepared in which the dry volume fraction of cuprous oxide ranged from 0.24 to 0.45 (60 to 80% by weight). The matrix was composed of 3 parts Vinylite and 1 part rosin.

The initial leaching rates of these paints were measured, and they were then extracted in sea water containing 0.1% sodium citrate. The citrate forms a highly soluble complex with the copper, which is therefore not reprecipitated as basic cupric carbonate; dissolution from the paint can proceed until substantial amounts of copper have accumulated in solution. After extraction, the panels were washed and their leaching rates were redetermined in ordinary sea water. Extractions in citrated sea water and leaching rate measurements in ordinary sea water were then repeated, alternately, several times.

The leaching rates are plotted in Figure 3 against the total amount of cuprous oxide removed as determined by analysis of the citrate solutions. This figure contrasts sharply with Figure 2, which showed that leaching ceases after extraction of 57 micrograms per sq. cm. when the volume fraction of toxic is 0.12. When the volume fraction is 0.24, the leaching continues until 1000 micrograms per sq. cm. have been extracted; when the volume fraction is 0.45, it continues until more than 4000 micrograms have been extracted. The leaching rate falls gradually, nevertheless, throughout the extraction.

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[2] The mass of surface-exposed toxic and, therefore, the life of a single layer of particles might be expected to increase somewhat with particle diameter. Electrolytically prepared cuprous oxide such as that used in these experiments has an average particle radius of the order of 1 micron.

Dissolution is evidently taking place from deep within the interior of the paint. Electrolytic cuprous oxide, such as that used in these paints, has an average particle radius of 1 to 2μ. A single layer of close-packed spheres, 2μ in radius with the density of cuprous oxide, would weigh 1460 micrograms per sq. cm.; this figure represents a rough upper limit for the mass of surface-exposed toxic. A more reasonable figure might be obtained by multiplying by the volume fraction of toxic, which would reduce it to one half or one third this amount. By the time 4000 micrograms per sq. cm. have been dissolved, therefore, the solvent has penetrated past several layers of particles.

The total amount of copper recovered in each set of citrated sea water extracts, calculated as cuprous oxide, was then compared with the loss in weight of the panel extracted. Table I shows this comparison for four paints of the series of Figure 3, and several other paints of different compositions. The loss of weight of the panel is practically identical in each case with the recovered copper expressed as cuprous oxide. These two quantities are also plotted against each other in Figure 4.

It is evident that only the toxic is removed under these conditions, and that the matrix remains intact on the panel. As a matter of fact, after extraction the paints were visibly bleached, the original bright red having paled to pink or gray; it was clearly apparent that only a skeleton of exhausted matrix remained.

TABLE I. EXTRACTION OF HEAVILY LOADED CUPROUS OXIDE PAINTS IN CITRATED SEA WATER

Vinylite in Matrix, %	Cuprous Oxide		Total Wt. Loss of Paint, μg./sq. cm.	Cu Recovered in Soln. as Cu_2O, μg./sq. cm.
	% by wt.	Volume fraction[a]		
50	70	0.33	3500	3100
	75	0.38	4600	4200
	80	0.45	5300	4600
	85	0.54	6700	6400
	90	0.65	7900	8000
75	70	0.33	2500	2300
	75	0.38	3700	3700
	80	0.45	4100	4100
	85	0.54	6600	6600
	90	0.65	6800	7000

[a] Calculated assuming the density of the matrix to be 1.25.

The extraction from the paint interior without loss of matrix, together with the sharp dependence upon the toxic volume fraction of the ability to release toxic beyond the surface layer, lead to the conclusion that, in the heavily loaded paints, the particles are in continuous contact. According to this interpretation, as soon as a particle becomes completely dissolved, another is uncovered beneath it. Even though the substance of the matrix be quite impermeable, extraction can proceed and toxic can eventually be removed from deep in the interior of the paint. As the toxic is dissolved, a tenuous skeleton of the matrix remains on the surface, with voids where the toxic particles were previously located.

BEHAVIOR OF HEAVILY LOADED PAINTS IN SEA

Further information concerning the availability of toxic from the interior of heavily loaded paint films was obtained by studying their leaching in the sea. Panels coated with various paints, in which the proportion of cuprous oxide varied from 60 to 90% by weight, were immersed in the sea for 3 months, and were temporarily removed at monthly intervals for leaching rate measurements in the laboratory. The panels were weighed and analyzed.

Table II. Leaching Rates of Cuprous Oxide–Vinylite Paints after Immersion in Sea Water for Various Periods

Wt. % Cu_2O	Wt. % Vinylite	Volume Fraction Cu_2O[a]	Leaching Rate, μg./sq. cm./day, after:			
			0	1 mo.	2 mo.	3 mo.
40	60	0.12	12	1	2	1
60	40	0.24	23	0	2	1
70	30	0.33	79	16	16	9
80	20	0.45	92	41	38	23
90	10	0.65	146	64	61	29

[a] Calculated assuming the density of the matrix to be 1.25.

Table III. Losses of Total Weight and of Cuprous Oxide during 3 Months in Sea Water

Wt. % Cu_2O	Wt. % Vinylite	Wt. % Rosin	Volume Fraction Cu_2O[a]	Loss, μg./sq. cm.	
				Total wt.	Cu_2O
70	15	15	0.33	2070	2150
70	22.5	7.5	0.33	1400	1750
70	30	0	0.33	670	1250
80	10	10	0.45	3700	3760
80	15	5	0.45	3070	3250
80	20	0	0.45	1430	1560
90	5	5	0.65	6440	6600
90	10	0	0.65	2970	3870

[a] Calculated assuming the density of the matrix to be 1.25.

Table II gives the leaching rate measurements for five paints in which the matrix was pure Vinylite. The leaching rate falls off as soaking proceeds, and the smaller the volume fraction, the sharper this decrease. When the volume fraction is less than 0.3, the leaching rate falls to a negligible value within the first month of immersion, an indication that only the toxic particles originally exposed on the surface are available for dissolution. These results thus parallel closely the data of Figure 3, obtained for accelerated extraction of paints in the laboratory.

The toxic dissolved could not be recovered for analysis in this experiment, but the total amount lost may be calculated from analysis of each panel at the end of the experiment. The loss of cuprous oxide, derived in this way, was then compared with the total loss of weight. Table III shows this comparison for three paints of the series of Table II and for several other paints of different compositions. The values are closely similar in nearly every case, an indication that in the sea, just as in citrated sea water in the laboratory (Table I), only the cuprous oxide dissolves while the matrix remains intact. The data are plotted in Figure 5.

These paints, originally bright red, develop a greenish color in the sea. It is believed to be due to the partial reprecipitation of cupric salts on the paint surface. Basic cupric carbonate, formed from the oxidation of cuprous oxide in sea water, has a much lower solubility than the latter; cupric oxychloride, which is also formed, has a negligible solubility (*2*). The presence of deposits of these salts would therefore be expected to depress the leaching rate. It may also explain the tendency for the weight loss to be slightly less than the cuprous oxide loss (Table III).

To assess the effect of such deposits, leaching in the sea may be compared with leaching in citrated sea water in the laboratory, where the precipitation of cupric salts is prevented by the formation of the highly soluble cupric citrate complex. This comparison was made for a paint consisting of 90% cuprous oxide and 10% Vinylite. The leaching rates are plotted in Figure 6 against the total amounts of cuprous oxide removed. The latter quantities, for citrated sea water extraction, were obtained from analyses of the citrate solutions as before; for sea extraction, they were obtained by numerical integration of curves of leaching rate plotted against time, after temperature corrections (*1*) were made to convert the leaching rates as measured in the laboratory to the prevailing temperatures of the sea. The validity of the temperature corrections is indicated by the fact that the two curves for experiments in summer (average sea temperature over a 15-day period 23.5° C.) and winter (about 0° C. over a 90-day period) lie fairly close together.

The curves for sea extraction coincide with that for citrate extraction up to removal of about 1000 micrograms per sq. cm. of cuprous oxide, but thereafter the leaching rate in the sea falls off more rapidly. After removal of 1500 micrograms cuprous oxide per sq. cm., the sea-soaked panels developed a greenish color, whereas the citrate-extracted panels retained their red color; even though the latter eventually became paler, they showed no evidence of deposit formation. It may be concluded that the fall of leaching rate in the sea is due not only to the imperfections in continuous contact of particles, which are thought to be responsible for the changes during citrate extraction, but also partly to the formation of deposits which impede leaching.

THEORY OF CONTINUOUS CONTACT

In the case of simple extraction (as in citrated sea water), without the formation of deposits on the surface of the paint film, a rough theoretical description may be made of the process of leaching by continuous contact of toxic particles. In a close-packed arrangement of spheres, each particle touches several others, and there is a complete chain of contacts extending through the structure. In hexagonal close packing, the volume fraction occupied is 0.74. For a cuprous oxide–Vinylite system, a volume fraction of 0.74 corresponds to 93% of cuprous oxide by weight, and this should be the maximum amount which could be compounded if the particles were spherical. In practice the volume fraction of cuprous oxide in the systems studied is always less than 0.74. The particles are undoubtedly not in perfect continuous contact; on the average, the probability that a given particle touches at least one other is less than unity.

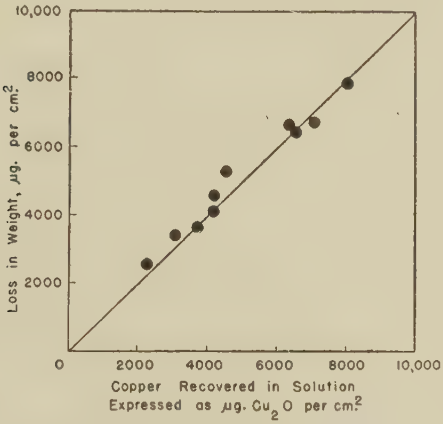

Figure 4. Loss of Weight during Extraction in Citrated Sea Water *vs.* Copper Recovered in Solution

To examine further the concept of contact probability, the toxic particles in a paint film may be thought of as arbitrarily classified into "layers" parallel to the surface, the thickness of a layer being equal to the average particle diameter. A layer contains, on the average, N particles per sq. cm. The probability that a particle in one layer touches (i.e., approaches within some small critical distance) at least one particle in another layer is denoted by p. Then the number of particles in the first subsurface layer which make contact with the surface layer is pN, and the number of particles in the nth layer which are connected by chains of contacts with the surface is Np^n.

When extraction has proceeded to the nth layer, only those particles which were originally in contact chains leading to the surface will be exposed to solvent action; the others at that level will be isolated by being enveloped in matrix. Hence the exposed particles at this point number Np^n. The leaching rate is proportional to the total area of exposed particles and, hence, on the average to their number:

$$L_n/L_0 = p^n$$

where L_0 = initial leaching rate
L_n = leaching rate after extraction has reached nth layer

The smaller p is, the more rapidly the leaching rate will fall as extraction proceeds deeper into the paint. Since p should decrease with decreasing volume fraction of toxic, the results of Figure 3 are qualitatively explained by this theory, although the data do not warrant a quantitative calculation.

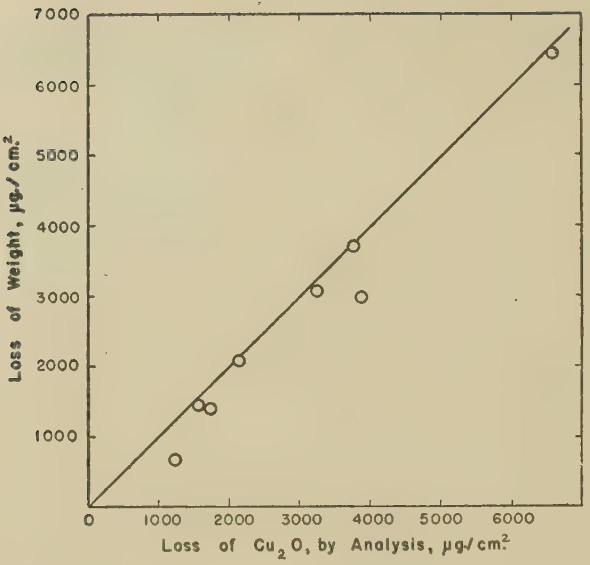

Figure 5. Loss of Weight during Immersion in the Sea *vs.* Loss of Cuprous Oxide as Determined by Analysis

The weight of extractable toxic in *n* subsurface "layers" of paint, plus the surface layer, is roughly given by:

$$d\rho v_1(1 + p + p^2 + \cdots + p^n)$$

where d = average particle diameter
ρ = density of toxic
v_1 = volume fraction of toxic in paint

The series converges for infinite n, to give $d\rho v_1/(1 - p)$. It follows that only a limited amount of toxic can be dissolved from a paint with the postulated structure, no matter how long the extraction is continued. The data of Figure 3 suggest that this is indeed the case. The maximum extractable toxic may be estimated by extrapolating these data to zero leaching rate; it ranges from 1500 micrograms per sq. cm. at $v_1 = 0.24$ to 5000 at $v_1 = 0.45$. The corresponding values of p, the contact probability, can be calculated from the preceding equation, taking d = 2 microns and ρ = 6 grams per cc. The results are $p = 0.81$ at a volume fraction of 0.24 and $p = 0.89$ at a volume fraction of 0.45. This indicates how contact probabilities of only a little less than unity may account for limited toxic extractability and hence limited paint life, and how very small differences in this probability may result in large differences in paint behavior.

An estimate may also be made of the depth to which extraction proceeds before the leaching rate falls below the critical antifouling value of 10 micrograms per sq. cm. per day. In Figure 3 this point is reached for a toxic volume fraction of 0.45 after 4700 micrograms of toxic per sq. cm. have been extracted. The number of "layers" penetrated can be found by solving the sum given in the preceding paragraph for *n*. In this case $n = 25$, so that the depth is 50 microns or about 2 mils. According to the theory, the paint film need be no thicker than this critical extraction depth; any additional thickness is wasted.

DISCUSSION

The extreme thinness of film which suffices for antifouling protection is one marked advantage of coatings of the type described in this paper, which maintain leaching by the mechanism of continuous contact of the toxic particles. The achievement of a strong, tough film with high erosion resistance is a further advantage.

The life of these paints—that is, the period over which toxic is released at a rate above 10 micrograms per sq. cm. per day and fouling is prevented—is, however, somewhat limited; it is not to be expected that the life can be prolonged by increasing the film thickness. It can, however, be extended by increasing the toxic loading to the highest point consistent with mechanical integrity. At high toxic loadings there is wastage at first because the initial leaching rate is many times greater than the minimum critical value. However, the deposition of cupric salts on the paint surface depresses the leaching rate and thus acts to some extent as an automatic curb to this wastage.

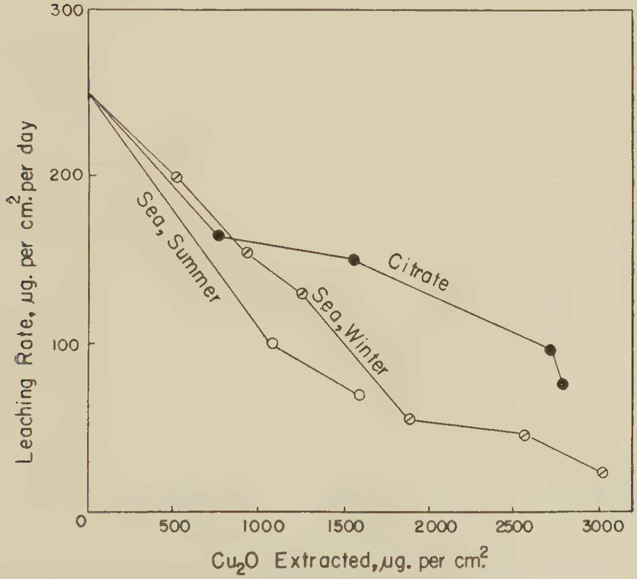

Figure 6. Changes in Leaching Rate of an Antifouling Paint Containing 90% Cuprous Oxide, during Extraction in the Sea and in Citrated Sea Water

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ACTION OF ANTIFOULING PAINTS

IV. Maintenance of Leaching Rate of Antifouling Paints Formulated with Soluble Matrices[1]

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An antifouling paint containing rosin or other acidic resins in the matrix loses both toxic and matrix simultaneously when immersed in the sea. The loss of matrix is shown to be the result of the dissolution of acidic resin in the slightly alkaline sea water. A paint of this sort maintains a uniform and adequate leaching rate because the dissolving matrix gradually exposes stores of toxic which were originally deep within the paint film. The substitution of neutral resins which are insoluble in sea water, for rosin or other resins which are soluble, may decrease or destroy the ability of the paint to maintain adequate leaching rates. A theoretical description of the simultaneous dissolution of toxic and matrix is presented; the effects of surface residues of insoluble matrix components on the dissolution of the paint are discussed. The toxicity of a paint which operates by this mechanism depends on the loading of the toxic ingredient and the solution rate of the matrix. The opportunity of making independent adjustment of these two variables permits great flexibility in designing a paint with the desired leaching rate

A PREVIOUS paper described the mechanism which permits the continued solution of toxic from paints containing toxic particles in continuous contact (*2*). In order to operate effectively through this mechanism, a paint must contain more than 30% cuprous oxide by volume.

Many antifouling paints give satisfactory leaching rates for long periods with much smaller toxic loadings, and their operation must depend upon some other mechanism. Several possible hypotheses have been suggested to explain the adequate leaching rates of these paints. Permeability of the paint film, erosion or exfoliation of the matrix, or dissolution of the matrix or one of its ingredients might conceivably afford a mechanism for continuous release of toxic. With the exception of permeability, these involve the simultaneous loss of matrix and toxic from the paint film.

This paper will describe the results obtained with various paints which lose matrix and toxic simultaneously when soaked in the sea, and present evidence that their maintenance of adequate leaching rates is associated with the dissolution of the matrix in sea water.

SOLUTION OF MATRIX INGREDIENTS

The fact that many antifouling paints lose both toxic and matrix when soaked in the sea can be established by analysis of exposed paint films. A series of antifouling paints was formulated to contain graded amounts of cuprous oxide in a cold plastic vehicle. Ground glass panels coated with these paints were weighed, immersed in the sea for two months, dried to constant weight, and reweighed. The paint films were analyzed for total copper before and after immersion. The copper contents of the paints and the losses of cuprous oxide and of total weight are given in Table I.

The concentration of cuprous oxide in the film decreased only slightly during the period of soaking, and all of the paints lost substantially more weight than can be accounted for by the loss of cuprous oxide. The additional decrease in weight reflects the loss of the paint matrix. This behavior may be contrasted with that of the continuous contact paints described in the earlier paper (*2*) in which none of the insoluble matrix was lost during sea immersion; the weight losses from such paints were equal to the losses of cuprous oxide.

That the loss of matrix from paints of the type referred to in Table I represents actual dissolution is suggested by the fact that many antifouling paints contain acidic resins, notably rosin. Such resins are soluble in mildly alkaline solutions, with formation of the corresponding salts, although they are insoluble in water or in acid solutions. In sea water, at pH 8.1, abietic acid and WW rosin have been found to have substantial solubilities of the order of several hundred micrograms per cc. (*6*). These solubilities have been found to be proportional to the hydroxyl ion concentrations, as would be expected if a soluble salt is formed. Studies

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[1] Previous papers in this series appeared in June (page 612), July (page 699), and August (page 806).

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of neutral resins including ester gum and other essentially neutral rosin esters, copper resinate, cumar resins, phenolic resins, and alkyd resins show that these compounds have negligible solubilities at the pH of sea water.

Studies of the rate of solution of matrix ingredients in sea water and in buffer solutions have afforded the following additional information on matrix dissolution (*6*):

1. The rosin dissolved from a coated panel agitated in sea water is of the order of several hundred micrograms per sq. cm. over a 24-hour period. The rate of solution is not constant, however, but gradually decreases with time.
2. The rate of solution of rosin increases with preliminary aging of the film in air, owing presumably to oxidation with the formation of more highly soluble products.
3. The presence of calcium and magnesium ions in buffer solutions and in sea water decreases the rate of solution of rosin, owing presumably to formation of insoluble compounds at the surface.
4. The rate of solution of an acidic resin is decreased by the incorporation of neutral resin.

It was also found that the matrices of certain antifouling paints applied as clear films dissolve in sea water at measurable rates. For example, the matrix of one paint of the cold plastic type dissolved in running sea water at a rate of about 100 micrograms per sq. cm. per day. Thus the hypothesis that the matrix, as well as the toxic, of an antifouling paint can undergo slow solution is supported by solubility data.

Table I. Copper Content and Loss in Weight and Cuprous Oxide of Cold Plastic Paints after Soaking in the Sea for 2 Months

Original Cu_2O, %	Final Cu_2O, %	Loss of Cu_2O, μg/sq. cm.	Total Loss of Wt., μg./sq. cm.
1.39	1.40	16	1303
2.52	2.36	112	2842
5.25	4.68	150	966
10.5	9.20	348	1254
15.6	13.6	712	2324
21.8	21.2	584	2273
28.1	25.9	665	1273
40.5	39.9	932	2044

Table II. Recovery of Steady-State Leaching Rate of a Cold Plastic Type Paint after Removal of Various Amounts of Surface Toxic in Sea Water Acidified to pH 4

Days in Sea Water at pH 4	Cu_2O Removed, μg./sq. cm.	Leaching Rate, μg./sq. cm./day, after Soaking in Sea Water for: 1 hr.[a]	4 hr.[b]	24 hr.[c]
1	41	2.2	4.7	14.1
2	64	4.9	8.9	14.5
3	74	2.5	8.1	12.5
4	83	4.0	5.6	12.7
5	116	1.7	3.4	..
7	153	0.0	2.0	11.5
8	172	1.7	2.2	10.8
9	172	0.0	2.7	12.0

[a] Calculated on the basis of 1-hour leaching.
[b] Calculated on the basis of 4-hour leaching.
[c] Running sea water; calculated on the basis of 4-hour leaching.

DEPENDENCE OF AVAILABILITY OF TOXIC ON MATRIX DISSOLUTION

Evidence that the availability of toxic in paints which lose both toxic and matrix upon sea immersion is associated with matrix dissolution is given by the following experiments.

Panels coated with a cold plastic paint were treated with sea water acidified with hydrochloric acid to pH 4. Under these conditions the surface-exposed cuprous oxide is rapidly dissolved, whereas the solubility of the acidic matrix components is negligible. Accordingly, surface exhaustion of the toxic takes place, just as in the insoluble Vinylite paints described previously (*2*). Leaching rates, measured by the standard procedure (*3*) in ordinary sea water after varying periods of acid extraction, are plotted in Figure 1 against the amount of toxic removed. The leaching rate became zero after the dissolution of 240 micrograms of cuprous oxide per sq. cm. This is the right order of magnitude for the quantity of surface-exposed toxic on a freshly painted surface (*2*). Clearly, only the surface toxic has been dissolved, and the mechanism which normally operates in the sea to maintain leaching from the interior of the paint film has not functioned in the acidified solution.

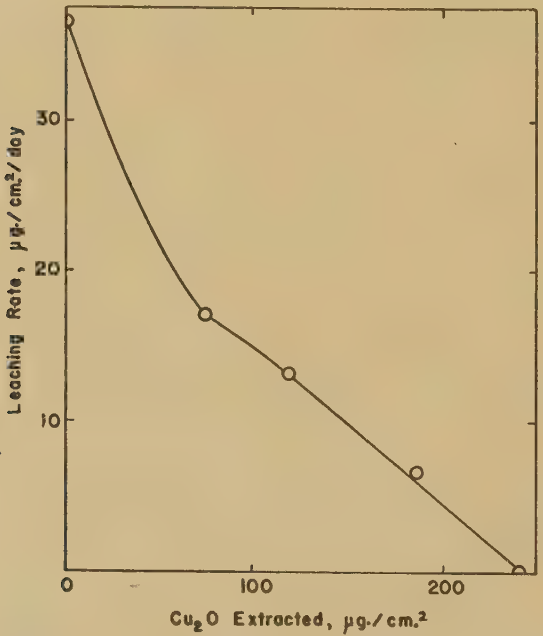

Figure 1. Leaching Rate of Cold Plastic Type Paint as Function of Amount of Toxic Removed in Acidified Sea Water (pH 4.0)

However, after the surface toxic has been exhausted, the ability of this paint to leach at an adequate rate can be rapidly restored by soaking in sea water. Panels which had been leached in the acid sea water (pH 4) were rinsed and returned to normal sea water, and the leaching rates measured after various times. The results of this experiment are given in Table II. The leaching rates of all of the panels increased during the first 4 hours of soaking in sea water, and all had reached values greater than 10 micrograms per sq. cm. per day by the end of 24 hours in sea water.

It is apparent that the exhausted surface has been regenerated by sea water soaking, a new layer of cuprous oxide particles has presumably been uncovered by removing the layer of matrix which remained after the acid treatment. The following experiments on regeneration in alkaline solution indicate that the dissolution of the matrix is responsible for the recovery of the leaching rate.

Panels coated with a cold plastic antifouling paint were first extracted in sea water acidified with hydrochloric acid to pH 4 and then stirred at 100 revolutions per minute in tap water adjusted to pH 11.5 with sodium hydroxide (*1*). The acid treatment was carried out for 3 days in three successive changes of solvent. The leaching rates of the paint were measured after the acid extraction and after various times in the alkaline solution. The results (Table III) show that the leaching rate increases rapidly after treatment with the strongly alkaline tap water. Comparison with the results in Table II, which were obtained on the same formulation, shows that the action of the solution at pH 11.5 is much more rapid than that of sea water at pH 8.1.

Panels coated with a number of effective antifouling paints were extracted, as described, in sea water acidified to pH 4 and for 3 hours in tap water at pH 11.5. The results show that the leaching rate increases to almost its initial value after 3 hours in the alkaline solution (Table IV).

The increase in the leaching rate of an acid-exhausted paint re-

TABLE III. EFFECT OF ALKALINE SOLUTIONS (pH 11.5) ON LEACHING RATE OF A COLD PLASTIC PAINT PREVIOUSLY EXTRACTED FOR 3 DAYS IN SEA WATER AT pH 4

Hours in Tap Water at pH 11.5	Leaching Rate in Sea Water, μg./sq. cm./day	
	After acid treatment	After alkaline treatment
1.0	3.0	14.3
2.0	2.1	22.6
3.0	3.7	38.3
4.0	2.8	39.4
5.0	3.3	37.5

TABLE IV. LEACHING RATES OF EFFECTIVE ANTIFOULING PAINTS BEFORE AND AFTER SUCCESSIVE ACID AND ALKALINE EXTRACTIONS

Paint	Leaching Rate in Sea Water, μg./sq. cm./day		
	Initial	After acid treatment	After alkaline treatment
1	45.6	3.4	38.3
2	54.3	7.2	44.5
3	36.1	1.3	29.4
4	40.1	0.9	36.3
5	29.0	1.1	23.0

sulting from treatment with alkali is attributed to the dissolution of a surface layer of matrix, which uncovers a new layer of cuprous oxide particles. The rapid regeneration of the leaching rate obtained in the solution at pH 11.5, compared to the sea water at pH 8.1, indicates that the mechanism of the regeneration is one of saponification and consequent dissolution of the acidic components of the paint matrices.

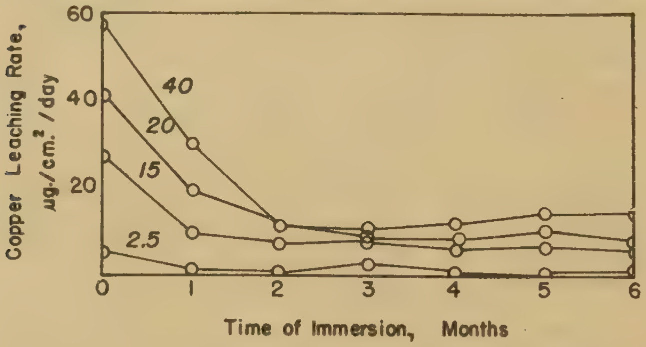

Figure 2. Leaching Rates of Cold Plastic Type Paints after Immersion in the Sea

Number above each curve gives the weight per cent of cuprous oxide in the paint.

The above experiments involve two successive extractions: (*a*) of toxic, under conditions where the solubility of toxic is enhanced and that of the matrix suppressed; and (*b*) of matrix, under conditions where the solubility of the matrix is enhanced and that of the toxic suppressed. It is also possible to extract a paint under conditions where the solubilities of both phases of the paint are high. Alkaline solutions of sodium glycinate and sodium chloride serve this purpose (*4*). The resin acids are held in solution by the alkaline buffer, and the copper is dissolved as a cupric glycinate complex ion. In such a solvent (0.025 *M* sodium glycinate, 0.48 *M* sodium chloride, pH 10.5), effective paints dissolve approximately a hundred times as fast as in steady-state leaching in the sea, until several thousand micrograms of cuprous oxide per sq. cm. have been removed. The leaching thus extends deep into the body of the paint. When the glycine extract is acidified and extracted with ether, substantial quantities of resin are recovered, an indication that the matrix has dissolved along with the toxic as leaching proceeds. Table V gives some examples of the amounts of toxic and matrix dissolved by this procedure. The figures show that substantial thicknesses of paint, many times the diameter of a toxic particle, have been removed by the treatment. The proportion of cuprous oxide dissolved to acid resin dissolved is usually close to the original proportion of cuprous oxide to rosin in the paint, an indication of simultaneous dissolution.

SOLUBLE MATRIX PAINTS IN THE SEA

Paints which are formulated with a soluble matrix generally reach a steady state of leaching after the first few months of soaking. After this time the toxic leaching rate of the paint remains essentially constant for long periods and, indeed, may remain the same until the paint has been completely dissolved from the surface. For any given matrix the value of the steady-state leaching rate depends upon the toxic loading of the paint. The leaching rates of a series of paints formulated to contain various amounts of cuprous oxide in a cold plastic matrix are plotted in Figure 2 against the time of sea immersion. The total pigment volume content of these paints was maintained at 12% by replacing cuprous oxide with magnesium silicate. As the cuprous oxide content is reduced, the steady-state leaching rate becomes smaller. In this matrix the minimum cuprous oxide loading which gives leaching rates of 10 micrograms per sq. cm. per day, the value necessary for the prevention of fouling (*3*), is about 15% by weight based on total nonvolatile content. A less soluble matrix would require a higher loading of the toxic; a more soluble matrix would give adequate leaching rates with less cuprous oxide in the paint.

Table VI shows the effect of using resins of varying acid number in a simplified paint formulation. The paints made up with resins having acid numbers of 125 or more gave good fouling resistance and had leaching rates which were generally in the neighborhood of 10 micrograms per sq. cm. per day. All of the paints made with less soluble resins (acid numbers of 60 or less) had low and inadequate leaching rates and fouled rapidly when exposed at Miami.

The partial substitution of neutral insoluble resins for the rosin of a satisfactory formulation also results in a decrease in leaching rate and antifouling performance. Table VII shows the leaching rates obtained with a series of paints in which ester gum was substituted for various amounts of the rosin of a simplified formulation. As the proportion of ester gum is increased, the steady-state leaching rate becomes smaller until the paint no longer gives satisfactory results. Here the use of more than 7% ester gum in the matrix (total neutral material of 40%) resulted in paints which gave poor fouling resistance and inadequate leaching rates. Similar results observed when phenolic varnish solids were substituted for rosin in this type of formulation were reported previously (*3*).

THEORY OF SOLUBLE MATRIX PAINTS

To summarize, we have the following evidence that many antifouling paints which lose toxic and matrix simultaneously maintain their steady-state leaching rates by dissolution of the matrix: (*a*) The acidic ingredients which are present in most antifouling paint matrices have substantial solubilities in sea water, and the matrices themselves can dissolve at rates which are of the same order of magnitude as the toxic leaching rates; (*b*) the mechanism which maintains steady-state leaching in normal sea water does not operate in acidified sea water, but is restored after the paint is returned to normal sea water and is rapidly regained by treatment with a dilute alkaline solution; (*c*) the entire process of steady-state leaching is enormously accelerated in an alkaline solution of glycine, in which the amounts of copper and acid resin dissolved are roughly in the same proportions as those in the

TABLE V. DISSOLUTION OF TOXIC AND MATRIX IN ALKALINE GLYCINE SOLUTIONS

(3 days in 0.025 *M* sodium glycinate, 0.48 *M* sodium chloride, pH 10.5)

Ratio of Cu_2O to Rosin in Paint	Amounts Dissolved, µg./sq. cm.		Ratio of Cu_2O to Resin Dissolved
	Copper as Cu_2O	Acid resins	
1.20	4460	2020	2.21
2.00	4500	2370	1.90
2.50	3160	1460	2.16
2.50	4600	1970	2.34

TABLE VI. LEACHING RATES OF PAINTS FORMULATED WITH RESINS OF VARIOUS DEGREES OF ACIDITY

Resin Used[a]	Acid No.	Copper Leaching Rates, µg./sq. cm./day, after Soaking							
		0	1 mo.	2 mo.	3 mo.	4 mo.	6 mo.	8 mo.	10 mo.
Maleic-dipentene	400	[b]	28	30	18	18	29	12	14
Staybelite	162	0	15	11	11	12	14	12	11
Rosin	160	12	10	22	10	14	14	10	9
Rosin-modified phenolic	140[c]	9	11	..	9	4	8	7	7
Yacca gum	125	29	11	12	9	6	7	11	8
Manila	60	5	6[d]	7[d]	12[e]	6[e]	5[e]	4[e]	..
Congo gum	60	6	2[d]	2[d]	2[e]	2[e]	2[e]	3[e]	3[e]
Dammar	25	6	4[d]	3[d]	3[e]	3[e]	2[e]	4[e]	3[e]
Kauri	16	8	6[d]	5[d]	3[e]	6[e]	3[e]	3[e]	..
Ester gum	8	12	4[d]	4[d]	2[e]	2[e]	..	..	..
Neville G	0	7	2[d]	3[d]	1[e]	3[e]	3[e]	4[e]	3[e]

[a] Paint composition, in per cent by weight, was: resin 25.0, Aroclor 1248 12.5, cuprous oxide 62.5.

[b] The initial leaching rate of this paint, measured after 2 hours in sea water, was 4000; this rate would have consumed the entire paint film in a day if it had continued.

[c] This acid number probably includes a contribution from insoluble acidic constituents, which accounts for the fact that the leaching rates are lower than would be expected from comparison with the other formulations.

[d] Paint fouled enough to be judged unsatisfactory when exposed the indicated time at Miami Beach, Fla.

[e] Panel exposure at Miami discontinued because of severe fouling.

TABLE VII. LEACHING RATES OF PAINTS, CONTAINING 62.5% CUPROUS OXIDE BY WEIGHT, IN WHICH ROSIN OF MATRIX WAS PROGRESSIVELY REPLACED BY ESTER GUM

Matrix Composition, %			Copper Leaching Rates, µg./sq. cm./day, after Soaking								
Rosin	Ester gum	Aroclor 1248	0	1 mo.	2 mo.	3 mo.	4 mo.	5 mo.	6 mo.	8 mo.	10 mo.
67	0	33	53	19	17	16	15	14	14	11	12
64	3	33	44	19	17	10	12	13	14	12	13
60	7	33	41	11	9	7	8	8	11	10	9
50	17	33	52	9	6[a]	4	5	5	7[a]	7[a]	8[a]
43	24	33	51	5[a]	5[a]	3[b]	5[b]	4[b]	5[b]	5[b]	5[b]
34	33	33	51	7[a]	5[a]	2[b]	4[b]	3[b]	5[b]	4[b]	5[b]
17	50	33	13	1[a]	2[a]	1[b]	3[b]	1[b]	2[b]	1[b]	2[b]
0	67	33	47	2[a]	2[a]	1[b]	3[b]	2[b]	2[b]	3[b]	2[b]

[a] Paint fouled enough to be judged unsatisfactory when exposed the indicated time at Miami Beach, Fla.

[b] Panel exposure at Miami discontinued because of severe fouling.

paint; (*d*) the substitution of neutral resins, which are insoluble in sea water, in place of acidic resins, which are soluble, decreases or destroys the ability of the paint to maintain adequate leaching rates in the sea. The antifouling properties of these paints are thereby destroyed.

A simplified theory of steady-state leaching by matrix dissolution may help to clarify the problems involved in the formulation of this type of antifouling paint.

If a steady state of leaching is attained in which the dissolution of toxic and the dissolution of matrix keep pace with each other, the rates at which they are lost from the paint must be proportional to their weight fractions in the mixture; thus the following equation must be fulfilled:

$$L_1/L_2 = w_1/w_2 \tag{1}$$

where L_1 and L_2 are the leaching rates of toxic and matrix, respectively, and w_1 and w_2 are their weight fractions in the paint. (If the toxic is cuprous oxide, L_1 is expressed in terms of cuprous oxide, not copper.) This equation is independent of any assumptions concerning the mechanism of dissolution or the geometrical details of the simultaneous exposure of both toxic and matrix.

Now, each leaching rate is a product of an intrinsic rate of solution and the ratio of the area exposed to the area considered as a plane:

$$L_1 = R_1 \frac{a_1}{A} \tag{2}$$

where R_1 is the intrinsic rate of solution of the toxic and a_1 is the actual area of toxic exposed on a paint surface of area A (considered as a plane). Similarly for the matrix,

$$L_2 = R_2 \frac{a_2}{A} \tag{3}$$

where R_2 is the intrinsic rate of solution of the matrix, and a_2 is the area of matrix exposed.

A schematic diagram of a section of paint film which maintains its steady-state leaching rate because of the solubility of the matrix is given in Figure 3 to aid in visualizing the meaning of the areas a_1 and a_2. If the assumption is made that toxic particles are disposed randomly, as Figure 3 shows, and the matrix surface is a plane intersecting them, then a_2/A (neglecting exposed matrix in the pits) is calculated to be equal to v_2, the volume fraction of matrix[3]. Combining with Equations 1 and 3,

$$L_1 = w_1 R_2 v_2 / w_2 \tag{4}$$

which is a theoretical expression for the steady-state leaching rate controlled entirely by matrix dissolution.

The intrinsic rate of solution of the toxic does not enter into this expression. Qualitatively this result would be expected when the matrix dissolves much more slowly than the toxic, as it usually does in practice, and therefore solely determines the over-all solution rate. In the hypothetical case of an insoluble pigment, the scheme on which Equation 4 is derived provides for the undermining of the pigment particles, which then drop off

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[3] The exposed matrix area is taken as the area, A, of the plane surface in Figure 3, minus the circles cut out by intersections with toxic particles. The sum of the latter areas, assuming random distribution of particles (N per unit volume), is:

$$\pi NA \int_0^{2r} (2rz - z^2)\,dz = \frac{4}{3}\pi r^3 NA = v_1 A$$

The matrix area is, therefore, $a_2 = A - v_1 A = v_2 A$.

as the matrix recedes. In this case Equation 4 would still be fulfilled, but the pigment would not pass into solution and L_1 would be a measure of the rate of loss of the insoluble pigment.

By means of Equation 4 the intrinsic rate of solution of the matrix of an antifouling paint may be calculated from the toxic leaching rate data. This has been done for the cold plastic paints containing various amounts of cuprous oxide (as in Figure 2) using the average of the copper leaching rates measured between the second and fifth months of exposure. The results of these calculations are given in Table VIII.

TABLE VIII. STEADY-STATE LEACHING RATES OF COLD PLASTIC PAINTS

Paint No.	w_1	w_2	Average Leaching Rate (2–5 Mo.), μg./sq. cm./day	R_2 (Calcd.), μg./sq. cm./day
4	0.04	0.74	2.2	46
5	0.08	0.72	4.3	44
6	0.14	0.70	6.9	39
7	0.20	0.68	9.2	36
8	0.24	0.66	11.3	35
9	0.30	0.64	12.7	31

The calculated values for the intrinsic leaching rate of the matrix are about 40 micrograms per sq. cm. per day, which is certainly the right order of magnitude, a value of about 100 having been obtained for the rate of dissolution of the pure matrix in running sea water. However, the fact that R_2 is not constant for the entire series indicates that the simplified theory presented here is not strictly applicable.

Equation 4 gives an indication of the matrix dissolution rate required to maintain an adequate toxic leaching rate in a paint of given composition. For example, the intrinsic matrix solution rates required to maintain a copper leaching rate of 10 micrograms per sq. cm. per day are given in Table IX for various loadings of cuprous oxide in a matrix whose density is 1.25. The required value decreases rapidly with increase in loading and becomes very small as the proportion of cuprous oxide approaches that required for continuous contact (*2*). Table IX also shows

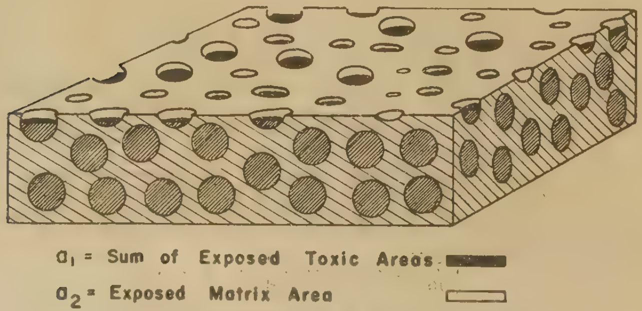
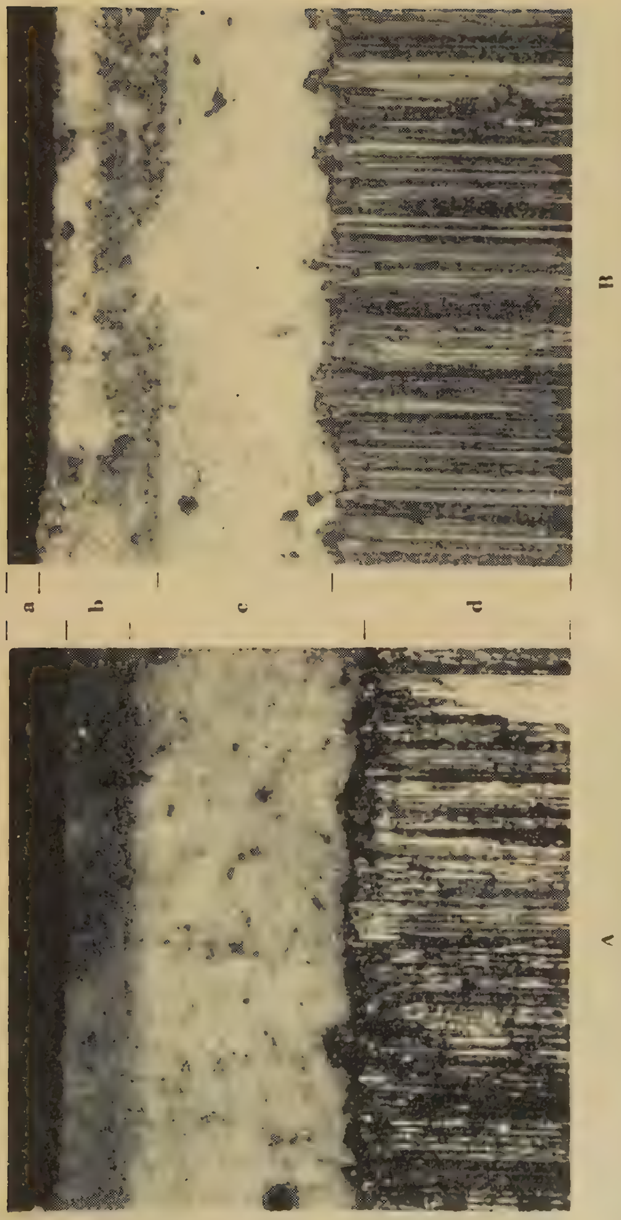

a_1 = Sum of Exposed Toxic Areas ▬
a_2 = Exposed Matrix Area ▭

Figure 3. Schematic Diagram of Paint Which Operates through Mechanism of Solution of Matrix



A

B

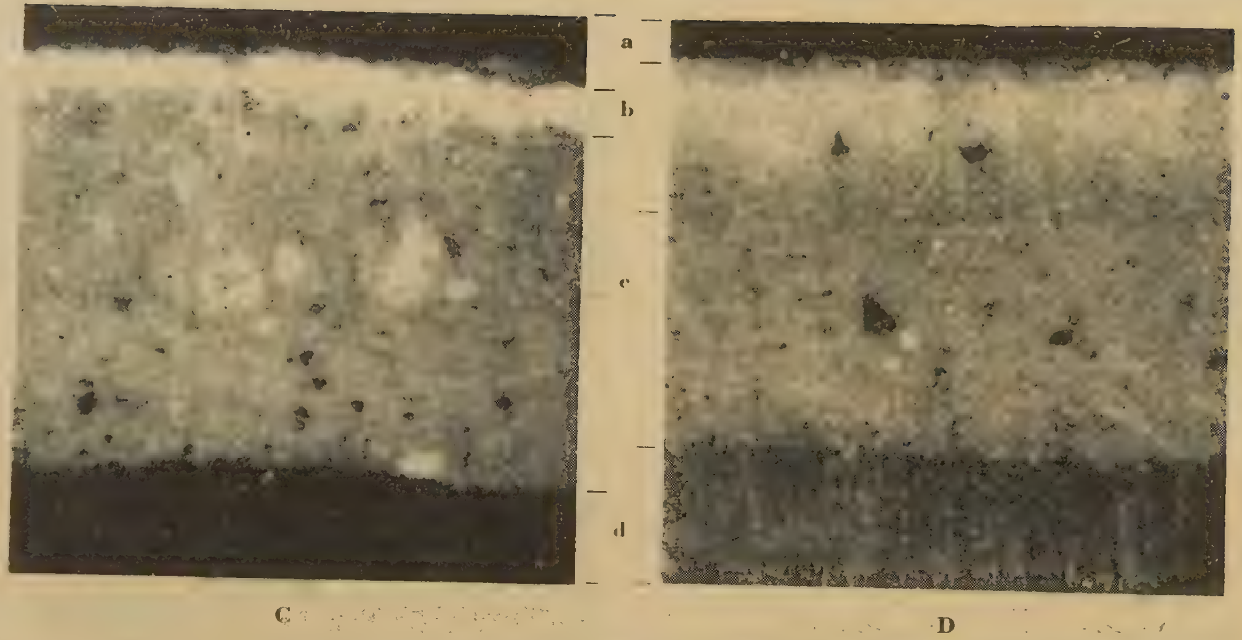


Figure 4. Cross Sections of Cold Plastic Antifouling Paint Films Applied to Steel Panels

The layers are identified as: (a) embedding material, (b) antifouling paint, (c) anticorrosive paint, (d) steel. A, B, C, D are described in the text.

that the weight of paint per unit area and the thickness required for a life of one year decrease rapidly with increasing loading with cuprous oxide.

SURFACE RESIDUES OF INSOLUBLE MATRIX COMPONENTS

When some satisfactory cuprous oxide paints are immersed in the sea, the soluble materials may be dissolved from the surface to leave a residual skeleton of insoluble ingredients. Insoluble salts of copper become incorporated in this layer. After the development of this surface deposit, the paint has a light green or gray color which can be scraped off to expose the original red color of the paint beneath. Recent experiments by Saroyan at the Mare Island Naval Shipyard indicate that, on hot and cold plastic paints which contain rosin and cuprous oxide, the green surface layer is largely composed of copper resinate.

The character of the surface deposits has been studied by microscopic examination of sections prepared by Lucas of the Bell Telephone Laboratories (*5*). Photographs of sections of paint films, including the steel plate, anticorrosive paint, and antifouling paint, are reproduced in Figure 4. Photograph A shows an untreated, cold plastic type paint. The antifouling paint is densely and evenly pigmented. B and C show sections of different preparations of the same paint after 1 and 6 months, respectively, of soaking in the sea. The toxic pigment has been extracted from the surface layer which, on visual examination appears green. After 6-month soaking the extraction of cuprous oxide has extended nearly through the entire depth of the film of antifouling paint. D shows the appearance of a section of antifouling paint which had been soaked for 3 days in a solution containing 0.025 *M* sodium glycinate and 0.48 *M* sodium chloride (pH 10.5). As described earlier in the article, this solution dissolves both cuprous oxide and soluble matrix about a hundred times as fast as they are dissolved in sea water. The cuprous oxide has been extracted from the surface of the paint by this solution and leaves a lighter colored layer which is pale yellow rather than the green observed on paints exposed in the sea. The surface layer of the glycine-extracted paints is apparently composed of the insoluble portions of the matrix. In the sea the interstices of this structure become filled with precipitated deposits of insoluble copper salts.

TABLE IX. INTRINSIC MATRIX DISSOLUTION RATES REQUIRED TO MAINTAIN A COPPER LEACHING RATE OF 10 MICROGRAMS PER SQ. CM. PER DAY, CALCULATED FROM EQUATION 4

Weight % of Cuprous Oxide	Matrix Soln. Rate Required µg./sq. cm./day	Weight per Unit Area Required for Life of 1 Year, µg./sq. cm.	Thickness Required for Life of 1 Year, mils
10	92	36,000	10
20	42	18,000	5
30	25	12,000	3
40	17	9,000	2
50	12	7,000	1
60	9	6,000	1
70	6	5,000	1

TABLE X. ACCUMULATION OF SURFACE RESIDUES BY PAINTS CONTAINING VARIOUS AMOUNTS OF NEUTRAL RESINS

(w_1 = 0.36; w_2 = 0.64; 28-day period between fourth and eighth week of immersion)

Neutral Resin Added	% Neutral Resin[a]	Total Wt. Lost, µg/sq. cm.	$\frac{\Delta T}{w_1}$	$\frac{\Delta M}{w_2}$	Surface Accumulation, µg./sq. cm.
Ester gum	25	1030	1250	910	220
	30	170	670	−109[b]	500
Copper resinate	14	1350	1970	1000	620
	18	2220	3190	1670	970
Hercolyn	13	615	1140	320	525
	18	935	1410	670	470
	24	228	945	−175[b]	715
	29	126	435	−49[b]	310
	36	516	840	335	320

[a] Including neutral material present in the rosin.
[b] Apparent gain in matrix.

The presence of surface residues and deposits give rise to changes in the paint which are not adequately described by the simplified theory presented in the preceding section. The magnitude of the deviations from the simplified theory can be determined by total analysis of the paint film after various times of soaking. The total loss of weight and of cuprous oxide from the paint can be measured; the loss of matrix is taken as the difference between these two values.

If Equation 1 is fulfilled at all times, even though the leaching rates of both toxic and matrix may change with time, over any given time interval the following relation should hold:

$$\Delta T/w_1 = \Delta M/w_2 \qquad (5)$$

where ΔT and ΔM are the quantities of toxic and matrix dissolved, respectively.

If, however, a residue of insoluble matrix components or a deposit derived from the toxic is left on the paint surface as the soluble components are dissolved, $\Delta T/w_1$ will always be greater than $\Delta M/w_2$, and their difference is a measure of the magnitude of the deposit and/or residue. The total amount of accumulated material is given by

$$S = \frac{w_2}{w_1 - w_1'} \Delta T - \frac{w_1}{w_1 - w_1'} \Delta M \qquad (6)$$

where w_1' = weight fraction of copper (expressed as cuprous oxide) in accumulated materials.

If the accumulation were pure copper abietate, w_1' would be 0.11, which is a probable upper limit. If the accumulation is largely matrix residue, $w_1' \cong 0$ and the equation reduces to

$$S = \frac{w_2}{w_1} \Delta T - \Delta M \qquad (7)$$

Results for a series of paints made up with cuprous oxide, rosin, and various amounts of different neutral resins (Hercolyn, ester gum, and copper resinate) are given in Table X. Here values of $\Delta T/w_1$ and $\Delta M/w_2$ have been calculated for the period from the fourth to the eighth week of immersion in the sea.

In every case the value of $\Delta T/w_1$ is greater than that of $\Delta M/w_2$, which shows that toxic has been lost in excess of its proportion in the paint. In fact, in several cases there has actually been an apparent gain in weight of the matrix over the interval specified. Table X also gives the total weight of material, S, which accumulated on the surface during the period of immersion, calculated by Equation 7. It is of considerable magnitude and, for some of the paints, even exceeds the total loss in weight during the interval of immersion. If w_1' is taken as 0.11 instead of 0, the values of S are increased by a factor of 1.44.

Many other measurements of this sort have shown that, in the simultaneous dissolution of toxic and matrix, the amount of dissolved matrix as calculated by difference is almost always less than that specified by the simple relation of Equation 1. Paints for which this is true have accumulated surface residues which may include insoluble matrix ingredients as well as precipitated salts of copper.

DISCUSSION

The toxic leaching rate of a paint which functions by virtue of a soluble matrix reaches a fairly constant value after a short period of soaking. The absolute value depends on both the rate of solution of the matrix and the proportion of toxic compounded in the paint. This permits the formulation of paints which have uniform copper leaching rates in excess of 10 micrograms per sq. cm. per day, the value necessary for the prevention of fouling, without an excessive waste of toxic. Furthermore, the leaching rate may be maintained at constant level as long as any paint remains on the surface. The life of paints formulated with soluble matrices can, therefore, be extended by increasing the thickness of the paint film.

In contrast to these observations, the leaching rate of a paint of the continuous contact type (2) decreases gradually with immersion and falls below the minimum value as soon as the critical depth is exceeded. Young, Schneider, and Seagren (7) presented theoretical curves of toxic losses from antifouling paints; their curve depicting a paint with a permeable matrix shows a steady decrease similar to the observed behavior of continuous contact paints.

The opportunity of making independent adjustments of two variables—the degree of toxic loading and the matrix dissolution rate—permits great flexibility in designing a paint with the desired leaching rate. It follows that a variety of satisfactory paints can be formulated with the same basic ingredients.

The major disadvantage of soluble matrix paints is that matrices of suitable solubility frequently have rather poor film characteristics. Careful formulation is required to obtain good physical durability and prevent premature failure by cracking, alligatoring, blistering, or erosion.

In the design of paints with soluble matrices, the proportion of toxic should be the minimum which, in a matrix with a given dissolution rate, will provide an adequate steady-state leaching rate. Any excess above this minimum will be wasted since the leaching rate will be unnecessarily high. In order to achieve maximum life, the thickness of the paint film should be the maximum consistent with economy and mechanical strength and integrity.

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Photography of the Ocean Bottom*

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I. INTRODUCTION

IN 1893 Boutan, working off the Mediterranean coast of France, took the first known underwater photographs, using a camera operated by a diver. In 1899 he constructed an automatic camera for operation at depths beyond the reach of divers, and clearly foresaw the important results which it could give; but apparently was never able to achieve them on account of the excessive weight of his apparatus and the lack of a suitable light source.

The first photographs with automatic cameras of which record has been found, showing objects on the ocean bottom in their natural environment, were made by the authors in 1940, following experiments begun in 1938. In view of the age old preoccupation of man with the mysteries of the ocean depths, of the scientific and practical value of the results to be obtained, and in view of the relative ease with which they may be achieved, this lapse of forty odd years is extremely astonishing.

Among those who have taken successful photographs at wading or diving depths, using manually operated cameras are: Barton, Bartsch, Bristol, Crosby, Dupont, Johnson, Longley, Miner, Reighard, Tee Van, Ward, Wasmund, and Williamson. Their work ranges from black and white time exposures through excellent color photography to full length motion picture features, and was naturally done in sheltered waters of limited depths. Almost without exception their light source was the sun. After World War I, an automatic camera, weighing about 1700 pounds, was constructed by Siebe Gorman and Company, Ltd., London, for the purpose of exploring for German traps in the flooded coal mines of the Lens district, France. Neither this type of work nor that done with cameras mounted on submarines will be considered further in the present report, which is concerned with photography in the ocean, using simple equipment, at depths not easily accessible to divers.

In 1935, Johnson constructed a camera which could be lowered to a depth of two miles; but the camera was lost before producing results. Harvey, in 1939, made a camera which gave good pictures of a target placed in front of it when lowered to depths as great as one and a half miles, but he obtained no photographs of marine life or of the ocean bottom. In 1935, Barton lowered his camera in the bathysphere to 500 fathoms, obtaining one picture of a spot of light which he believed was produced by a deep sea fish. The experiences of these three men, the first since Boutan to work with automatic

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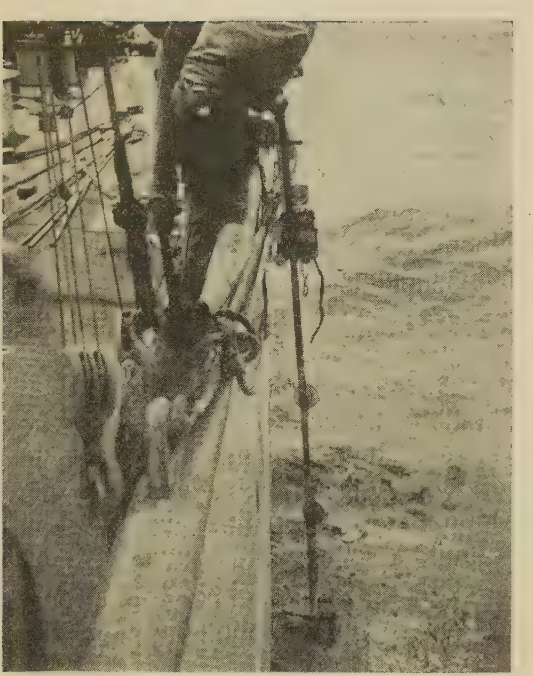

FIG. 1. Free floating camera, Type II, being taken aboard ship after a lowering.

cameras, confirm the opinion of the authors that the principal problems in underwater photography are not optical in character, nor of camera design. The problems are to find an interesting subject, and to put the camera in focus with it, to provide proper illumination, to hold the camera reasonably steady while the exposure is made, and to get the camera back afterwards.

The authors have met these conditions by using cameras pointing vertically downward and actuated by contact of a trigger with bottom, the distance of the trigger from the camera determining that for which the camera is focused. The light source, in a suitable reflector, is placed between the camera and trigger as far below the camera as possible, and synchronized with the camera shutter. The ocean bottom and the first few feet of water above it are so much richer in life and form than the body of the water that a random photograph made with the camera focused on bottom is almost certain to give valuable information, whereas one made in mid-depth is almost certain to be a blank.

It is convenient to classify all automatic cameras as "suspended" and "free floating" cameras. Suspended cameras are made heavier than water and are lowered and raised by means of wires. Free floating cameras are made lighter than water, by the addition of floats if necessary. They are taken down by ballast which is later released, allowing the camera to float to the surface. The exposure is always made to occur when the camera is the desired distance above bottom, by a bottom-actuated trigger placed at that distance from the camera.

Free floating cameras have the advantage of taking a series of pictures while remaining motionless in the interval between reaching bottom and releasing the ballast. This allows instruments lowered with the camera, such as compasses, current meters, etc., time to come to equilibrium before being photographed. Suspended cameras are most useful when it is desired to lower and raise a camera quickly over one particular spot, such as a sunken wreck. In deep water, suspended cameras have the disadvantage that the weight of the wire becomes too great for the operator to tell when the trigger weight has hit bottom and if an excess of wire is paid out, kinking is likely to cause the loss of the instrument.

Four types of free floating and suspended cameras have been designed and used by the authors from 1938 to the present. Type I, the first of the series, was free floating, enclosed in an aluminum case designed to go to depths of 3000 fathoms (about three miles) and to take a continuous series of pictures throughout its period of submergence. Incandescent light bulbs were used and ballast was released by the solution of a block of salt, allowing the buoyancy of the camera to bring it to the surface, the whole procedure taking about three hours. Unfortunately, this camera was lost on its third lowering. One series of pictures of the bottom was obtained with it, however, at a depth of 2700 fathoms.

Type II was also a free floating camera, constructed for depths of 1100 fathoms (about 1 mile), and with a ballast releasing mechanism actuated by clockwork. Figure 1 is a photograph of this instrument. It consisted of a Pyrex glass test tube three feet long and six inches in diameter, containing a modified Argus camera, and designed to take two pictures on each lowering, one 30 seconds after striking bottom and one 30 seconds later. By 1940, more than 100 clear pictures showing the ocean bottom and various forms of marine life had been taken with this camera, to depths of about 500 fathoms. Information was also obtained as to the force and direction of ocean currents by lowering various measuring instruments attached in the field of view of the camera and, in some cases, samples of the ocean bottom were taken simultaneously by an attached sampler. This camera was lost on being sent to 1500 fathoms, and is believed to have collapsed under the pressure.

Type III was a suspended camera, mechanically actuated by a trigger which hung below it. It made an exposure instantly on contact of the trigger with the bottom. Several variations of this camera have been built and more than 1000 pictures have been taken with it to investigate wrecked ships on the ocean bottom.

Type IV was a suspended camera, lowered by means of an insulated wire. Exposure occurred when an electric impulse was sent down the wire. This camera has been used in several special applications.

Every one of these underwater cameras consisted fundamentally of a water-tight box with a glass window, enclosing a camera of conventional design. In most cases, a spring motor was provided to advance the film and to operate the the shutter, so that a number of pictures could be taken without opening the case. All the cameras were of light enough construction for one man to handle conveniently over the side of a ship—an almost essential requirement.

In earlier underwater photography by artificial light, the light source has been placed as near as possible to the camera, illuminating the entire body of water between camera and subject, and allowing light scattered back by the water to be superimposed upon that returned by the subject. The authors have found it greatly preferable to place the light source well below the camera, close to the subject, and to screen it so as to illuminate the minimum amount of water. This arrangement not only decreases the difficulties arising from the scattering of light by water, but also provides side lighting on the subject, which may bring objects into relief in areas where the bottom is uniform in tone.

Up to the present time, the problem before the authors has been to find a tool with which to achieve an acceptable result in the shortest possible time, rather than to make a systematic investigation of the many factors which influence underwater photography. However, much information has been obtained and the techniques and instruments have been considerably developed. Application of the method has already been made in biological studies of marine plants and animals, determination of the geological characteristics of the ocean bottom, oceanographic measurements, and in the identification and salvage of wrecked ships.

II. OPERATION OF FREE FLOATING AND SUSPENDED CAMERAS

1. Free Floating Camera

This camera is represented in Fig. 2. The instrument is dropped over the side of the ship and allowed to sink freely to bottom under the influence of the ballast. Contact with the bottom actuates the trigger which releases a clockwork in the camera. The clockwork causes the first photograph to be made after 30 seconds and the next one 30 seconds later. It then actuates the electromagnetic ballast release, allowing the float to bring the instrument to the surface. It is well to include a safety clock which will release the ballast after a suitable length of time in case of failure of the regular mechanism. For use in depths of less than 100 fathoms, a fish line may

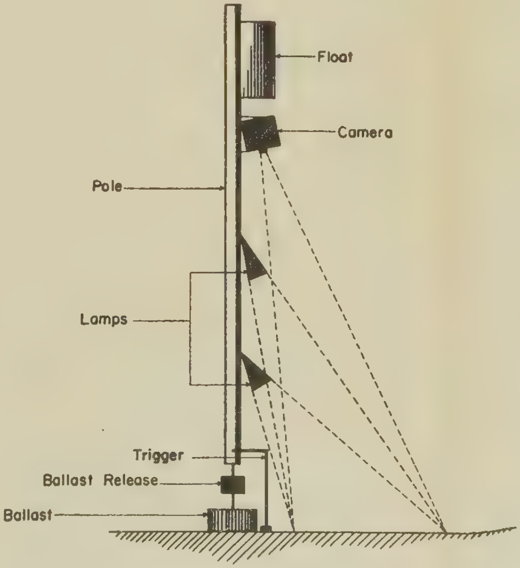

FIG. 2. Schematic diagram of the free floating camera.

be attached to the camera to pull it to the ship after it has reached the surface. This feature is particularly desirable during the hours of darkness. Compasses, current indicators, bottom samplers, etc., may be added as desired in the field of view of the camera.

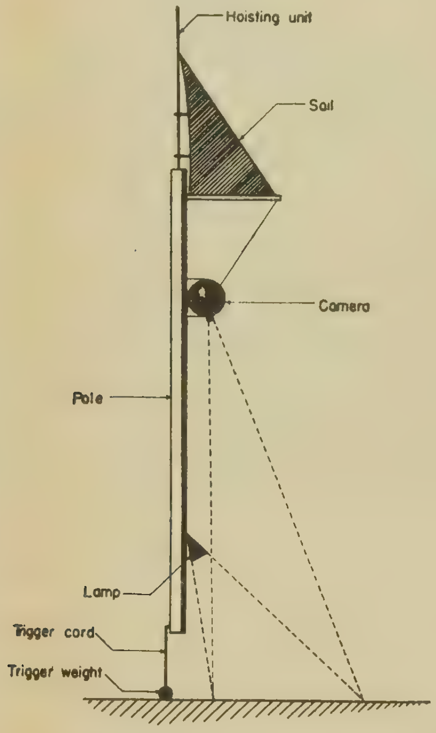

FIG. 3. Schematic diagram of the suspended camera.

2. Suspended Camera

This camera is represented in Fig. 3. It also has its components arranged along a vertical pole. It is lowered by means of a wire, and the speed of lowering is reduced just before it reaches bottom. A trigger weight is suspended below the instrument at any desired distance, and the camera is focused for approximately $\frac{3}{4}$ of that distance to allow for the refraction of light by water. The moderate downward motion of the camera at the instant of exposure usually does not interfere with its performance. However, even a slight rotation about the vertical axis will ruin the pictures. This trouble is minimized by use of a small piece of canvas rigged like a sail, as shown in the drawing.

It has been decided that, for suspended cameras, it is preferable to take only one picture on each lowering, and a latch has been provided so that only the first release of tension in the trigger line will actuate the camera. It then must be raised to the surface for resetting the latch before the next picture is taken. This is necessary because the roll of the ship frequently produces multiple contacts of the trigger weight with bottom during a single lowering, which creates confusion in identifying the pictures on each strip of film.

III. DETAILS OF CAMERA CONSTRUCTION

1. Main Seal of Watertight Camera Case

For cameras designed for depths of more than 100 fathoms, the principle of the main seal is to confine a rubber gasket so that it cannot flow under the effect of great pressure. Two such systems are shown in Figs. 4 and 5. The gasket is seated and brought to an initial pressure by the screws, rendering the case watertight in shallow depths. As the camera descends in the water, the total pressure on the unsupported area of the head is applied to the gasket, which would flow were it not retained by the side walls. It has been found that an ordinary rubber gasket can be adequately confined if the clearances are as small as 0.001 in.

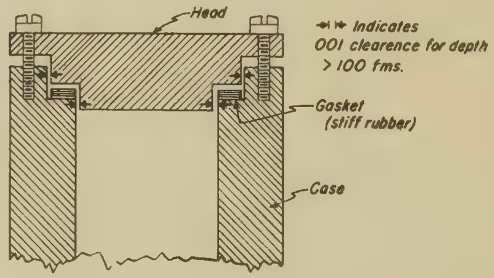

FIG. 4. Main seal of watertight camera case, for depths greater than 100 fathoms.

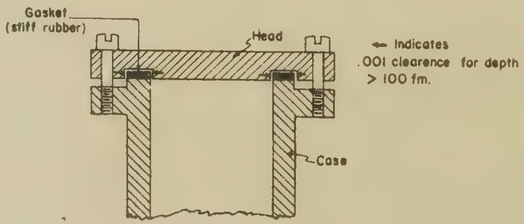

FIG. 5. Alternate main seal, for depths greater than 100 fathoms.

In water depths of less than 100 fathoms, stiff rubber has sufficient strength not to flow through spaces as great as 0.005 in. Thus, the same types of seals can be used as those for deep water work, but with larger spaces, which makes it very much easier to fit the head to the case.

2. Window Design

For water depths of more than 100 fathoms, the window is seated on a narrow ridge of metal as close as possible in size to the hole in the case. (See Fig. 6.) The ridge is cut as flat as possible and the window is ground on to it with FFF carborundum. After both parts have been ground flat, the carborundum is removed and cleaned, and a thin layer of grease is put on before the window is seated. The window is held in position by a retaining ring screwed to the case (shown in Fig. 7). Slots deeper than the window are cut in this ring to allow the air to escape from the space in front of the window. Otherwise, trapped air may form a bubble in this space and spoil the picture. This is the only method of fitting a camera window found practicable in deep water.

For depths of less than 100 fathoms, a gasket may be used, as shown in Fig. 8. A small raised portion of the seat inside the gasket keeps it from squeezing inwards. This raised portion is not tall enough to touch the window.

These windows have been made of ordinary plate glass inspected for reasonable flatness. The thickness required for given depths of water and diameters of window is calculated from a standard formula:

$$T/r = .45h/S$$

where

T = thickness,
r = effective radius of window,
S = stress in window in pounds/square inch,
h = depth of camera in the sea.

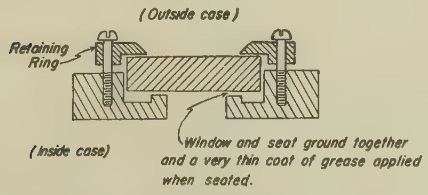
(Outside case)
Retaining Ring
(Inside case)
Window and seat ground together and a very thin coat of grease applied when seated.

FIG. 6. Seating of window in camera case, for depths greater than 100 fathoms.

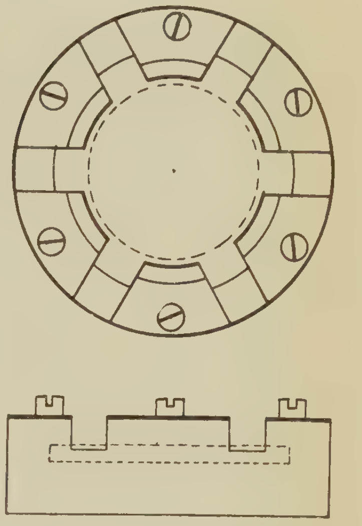

FIG. 7. Window retaining ring.

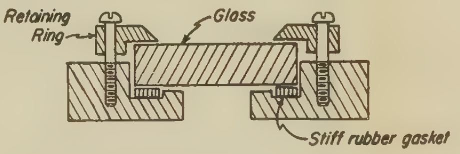

FIG. 8. Seating of window, for depths less than 100 fathoms.

Curves showing T/r for maximum stresses from 1000 to 100,000 pounds/square inch in disks with edges supported but not clamped, at depths from 100 to 40,000 feet are shown in Fig. 9.

The possible advantages of using curved windows have not yet been investigated. It has been suggested that the errors introduced by the transition of light from water to glass to air in front of the camera lens are analogous to those introduced by the cover glass in microscopy, and that they could be corrected by the same methods.

3. Condensation of Fog on Window

The air at sea is saturated with moisture and is generally warmer than the water in which the camera is lowered. Hence, condensation is likely to occur inside the camera case. During a single lowering, the metal parts of the case cool sufficiently fast to take all the condensation before any occurs on the glass. However, if repeated lowerings are made, the glass may become sufficiently cooled, and the metal sufficiently

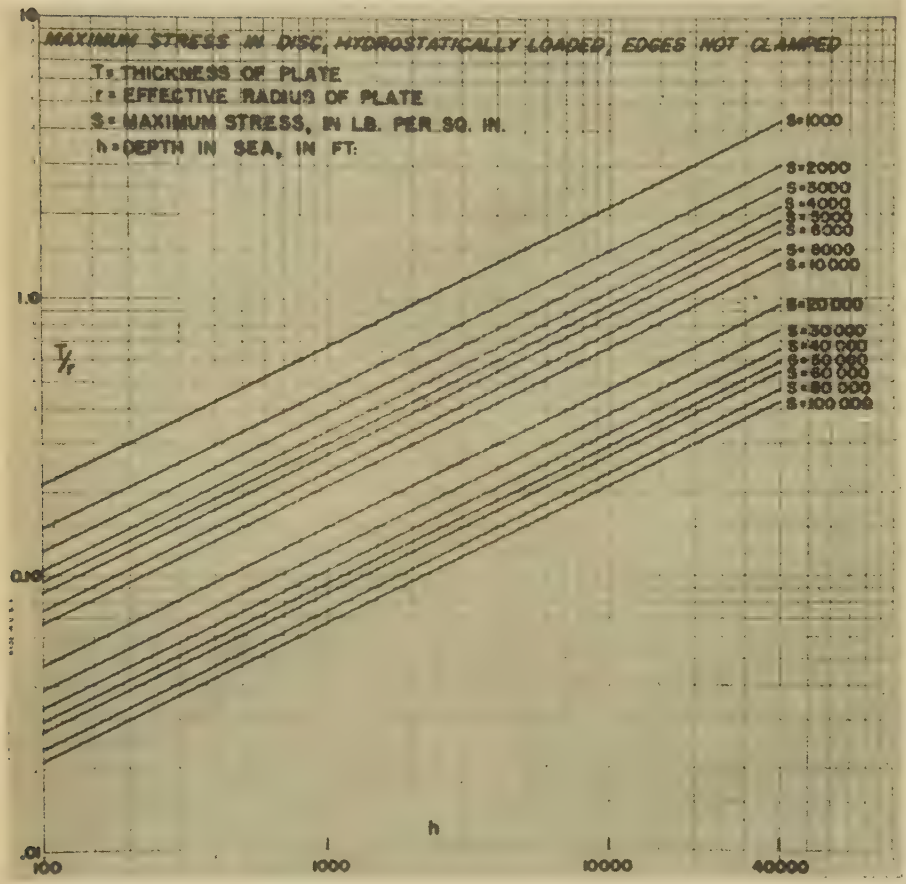

FIG. 9. Curves for maximum stress in disk hydrostatically loaded, edges not clamped.

warmed between lowerings, to cause the moisture to move from the metal to the glass of the window, forming a fog in front of the camera lens. Two methods of eliminating this difficulty have been tried. The first, filling the camera case with dried air, was discarded because of the complication of the apparatus and the necessity for valves, potential sources of leakage, in the case. The simplest and most practical method is to place a small bag of some drying agent, such as calcium chloride, inside the case to absorb the moisture. This precaution is unnecessary if lowerings are being made only occasionally.

4. Insulated Electrical Connections

There are several variations of the main system of making an insulated electrical connection through the camera case. A diagram of one is given in Fig. 10. The object of the system is to apply the tapers so that the pressure aids in making the watertight seal. The through connection is usually made of brass, since it is a good conductor and withstands sea water corrosion. The external insulator is usually made of Lucite because of its properties of plastic flow, but any other similar material can be used. Materials which are prone to fracture are not satisfactory for this tapered insulator. The internal insulator is made of some hard material such as formica.

5. Light Sources

Some photographs have been taken by sunlight at depths of 100 feet in very clear water, but in general it is necessary to provide artificial illumination. The light source found most satisfactory is the photo-flash bulb, because of its low electrical power requirements. Typical No. 22 flash bulbs will withstand the pressure at 60 fathoms, and the small size flash bulbs, such as the No. 5, can be used without protection to about 650 fathoms. It has also been found that no electrical insulation from the water is necessary for a conventional socket, if six volts are used to fire the flash bulbs, provided no large areas of metal in the ungrounded side of the electrical circuit are exposed to the water. The effective amount of exposed area can be greatly reduced by greasing the bulb sockets.

For depths greater than 650 fathoms, flash bulbs have been protected from the pressure as shown in Fig. 11. The insulated electrical connection is a variation of the fundamental system described above. The glass cup which protects the flash bulb from the pressure is made from the sediment cup of a standard automobile fuel system. The lip of the cup is ground to fit its seat, and a small amount of grease placed on the seat is sufficient to seal it.

Some incandescent bulbs have been specially made, through the courtesy of the General Electric Company. These operated on 12 volts and were made in Pyrex envelopes shaped like test tubes, with an inside diameter of two inches and a wall thickness of $\frac{3}{16}$ inch. These bulbs were used in Type I camera described above and worked satisfactorily to depths of 3500 fathoms. Two motor cycle storage batteries were used to operate these bulbs, the normal caps being replaced with caps to each of which a small rubber balloon was attached. The batteries were overfilled with liquid and the balloons permitted an equalization of pressure so that no pressure-proof case was needed. The electrical connections were waterproofed with tar and rubber tape and formed a bulky power supply, somewhat inconvenient to handle on the deck of a ship. Its weight in water, however, was not excessive. The electrical characteristics of the storage battery under the pressure of 8000 pounds to the square inch were normal.

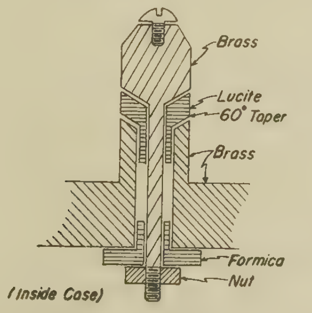

FIG. 10. Insulated electric connection through camera case.

The Kodatron flash lamp has been used in shallow water, but the cable losses are so high and the cable so heavy that it is impractical to use lengths of more than 150 feet. The necessary power supply and conversion unit are so large that, if put in a pressure vessel, they make a bulky apparatus extremely difficult to handle, and practically eliminate the possibility of using free floating cameras.

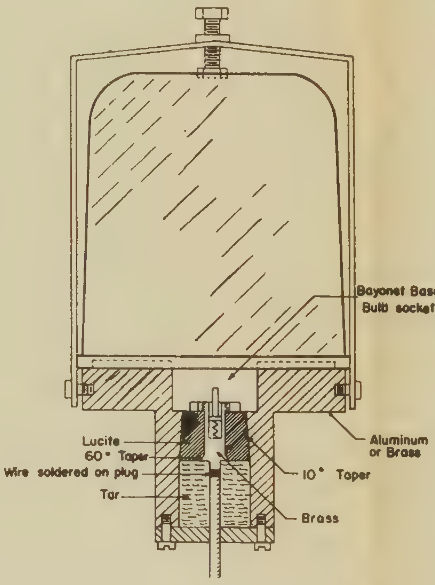

FIG. 11. Pressure proofed light bulb socket.

6. Sail

Suspended cameras tend to rotate as they are lowered, on account of twists in the wire. Their own motion through the water may also produce a torque. To eliminate the ill effects of camera rotation, a small sail as shown in Fig. 3 has been found effective, as it slows down the rotation to a negligible point. Free floating cameras may be allowed to rest on bottom until they come to equilibrium before making the exposure, but this is impossible with suspended cameras.

7. Ballast Release

Two types of ballast release, one electromagnetic and the other depending on the solution of a salt block, have been used with the free floating cameras. The first type consists of an electromagnet, which will withstand deep submergence in salt water, and can trip a trigger and release the ballast when actuated by batteries located inside the camera. The batteries are switched into connection with the magnet as the final operation in the cycle performed by the clockwork control system. This type of release is used in situations where precision in controlling the time of release is desirable.

A very useful arrangement for releasing the ballast, depending for its action on the solubility of salt, is illustrated in Fig. 12. Compressed blocks of salt, such as those made for the use of cattle, are cut into cubes about 1½ inches on a side. Each cube is placed in a cloth bag whose permeability to water determines the time required for the dissolution of the salt. This bag of salt is tied to the ballast, but is passed through a hole in a plate attached to the camera in such a way that when the salt is practically dissolved the plate slides over the bag, releasing the ballast and permitting the camera to rise to the surface. During descent to bottom the flow of water past the salt bag increases the rate of solution, which is obviously undesirable, particularly in deep water. Thus a shield is provided which protects the bag of salt from the water during the descent and which falls away from it when the camera reaches bottom. The merits of this device are that it is cheap, reliable, foolproof, and adds very little weight to be lifted to the surface.

8. Buoyancy of Floats

Glass, metal, or wood floats of conventional design may be used on the free floating cameras for depths up to about 100 fathoms, but for great depths only two schemes have proved successful. One depends on the structural properties of glass and the other on the buoyancy of gasoline.

As mentioned above, a glass camera case was constructed which had the required buoyancy and also the strength to withstand 1100 fathoms submergence. It is possible to design spherical vessels of glass or aluminum alloy which will retain adequate buoyancy at the ocean bottom, and these are probably the most desirable floats for use in great depths.

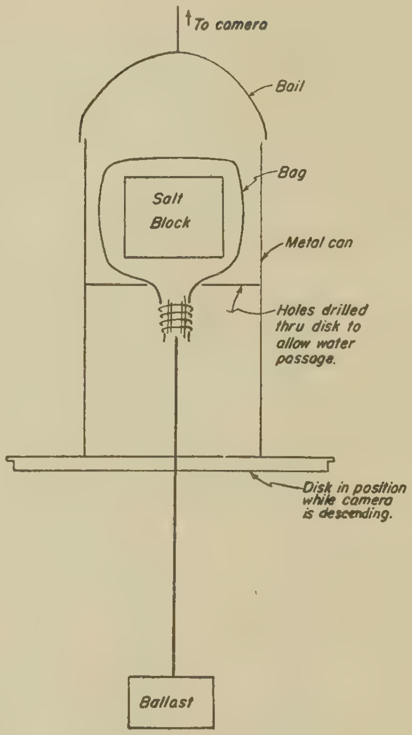
To camera
Bail
Bag
Salt Block
Metal can
Holes drilled thru disk to allow water passage.
Disk in position while camera is descending.
Ballast

FIG. 12. Chemical ballast release, using salt block.

An inexpensive and efficient float is made by the use of gasoline, although the fire hazard makes this type undesirable in the eyes of ship owners. Sealed metal containers may be used, provided their form and structure is such that they can tolerate the volume shrinkage due to changes of temperature and pressure without springing leaks. The well-known rectangular five-gallon tins will suffice, and give about ten pounds lift. If rigid containers are used, a vent must be left at the bottom of the float to admit water as the float descends. The most satisfactory gasoline floats are flexible bags made of fabric and neoprene. The largest float which has been required to date held about 20 gallons of gasoline.

9. Locating Free Floating Cameras

In deep water, the free floating cameras may remain several hours submerged before returning to the surface. During this time the ship may be drifting at two or three miles per hour in an unknown direction, and without some aid in location the camera would never be found on the surface of the water. Small radio transmitters on the floats have been suggested, but the opportunity to try them has not offered itself. The problem has been solved by using a number of small auxiliary free floating bodies, dropped at the same time as the camera and timed to surface at intervals of about 15 minutes throughout the period of submergence of the camera.

IV. TRANSPARENCY OF SEA WATER

1. The Role of Transparency in Underwater Photography

The term "transparency" as applied to sea water in connection with underwater photography is used in a rather loose and qualitative sense to describe the suitability of the water for taking photographs through it. The two properties of the water susceptible of exact definition, and which control the transparency in some complicated way, are the coefficient of absorption, α, and the coefficient of scattering, β. By definition α is the fraction of light absorbed (i.e., converted into heat and other forms of energy) and β is the fraction scattered in traversing a path of unit length. Clarke and James have reported that filtering oceanic water brings its transparency up to approximately that of pure water, indicating scattering as the principal cause for loss of transparency. But in coastal water there is an unspecified dissolved substance which impairs the transparency even after filtering. Obviously the absorption of light places no theoretical limit upon the distances at which photographs may be made, for the effect of loss of light may be overcome by the use of stronger sources, faster lenses and emulsions, and longer exposures. If the only result of scattering were the loss of the scattered light, the effects of this action could be overcome by the same means. But the scattered light interferes further with photography because some of the light scattered by the water will enter the camera and reach the photographic plate. It is evident that there will be loss in the quality of the photograph when any appreciable fraction of the light reaching the plate comes from scattering particles in the water, and that no photographs of the subject will be obtained if too great a fraction of the light received is the result of scattering. The values of these two limiting fractions depend on the albedo of the subject, the contrast present in it, and the resolution desired in the photograph.

The angular distribution of the scattered light with respect to the direction of the incident beam is of importance in considerations of possible methods of reducing the effects of scattering. It is convenient to distinguish between scattering of the direct light, which involves scattering angles mostly greater than 90°, and that of the light reflected from the subject which involves scattering angles mostly smaller than 90°. There are two methods of reducing the former type of scattering which are not applicable to the latter type. The first of these has been employed with good results from the outset. It is to place and shield the light source so as to reduce the illumination of the water to a minimum. The second is to interpose suitably oriented polarized screens in front of the source, the camera, or both. Some advantage has been gained by this method, but not enough to lead the authors to adopt it.

The ill effects of both classes of scattering can be reduced by a suitable choice of the wave-lengths of the light used. Very little experimental evidence is available on the variation of scattering coefficient with wave-length or on the angular distribution of scattered light, and information about the nature of the scattering particles is not sufficiently complete to permit reliable theoretical estimates of these factors. However, it is reasonable to expect that the scattering will be less for longer wave-lengths and photographs in dirty water with infra-red light have shown definite improvement over those made without the use of filters. Although these experiments were only of a tentative nature and very little work has been done by the authors with infra-red photography, it is their opinion that, except in very special instances where there is much to be gained by taking photographs at extreme distances, the gains achieved by the use of infra-red illumination do not outweigh the nuisance involved in using it. The authors believe that, in general, it is preferable to take a greater number of pictures at a short distance using ordinary light than to take fewer pictures at greater distances with infra-red light.

2. The Use of Transparency Measurements

The simplest and most convenient apparatus which has been used for the estimation of transparency is the well-known Secchi disk, a white disk 20 cm in diameter. The depth at which this disk becomes invisible when lowered over the side of a ship in daylight is known as the Secchi disk reading. This varies from about one foot in the dirtiest harbors to as much as 150 feet for some mid-oceanic regions. The Secchi disk reading undoubtedly depends upon a combination of many factors, such as the absorption coefficient and the coefficient of backward scattering for the water, the intensity and angular distribution of the daylight, the state of the sea, and the reflectivity of the sea surface. Obviously most of these factors are not significant in underwater photography, particularly if the light source is placed near the subject and screened to avoid unnecessarily illuminating the water between the subject and the camera. A measurement more analogous to the actual photographic application would be the distance at which a *light source* at night could be seen in some specified detail. This measurement has but little practical value for underwater photography, since it is restricted to use during darkness.

The work of the authors has, however, established that, for water in which the Secchi disk distance is 40 feet or less, the maximum distance for satisfactory photography is about half the Secchi disk reading provided the light source is placed near the subject; otherwise less than half. Greater distances have not been attempted in clearer water because the information to be determined from the photographs did not require this, and because the readily available light sources would not properly illuminate a larger area than that of the field of view of the camera at a distance of 20 feet. It is reasonable to use the rule that maximum camera distance is half the Secchi disk distance until there is an opportunity to make experiments for testing the point.

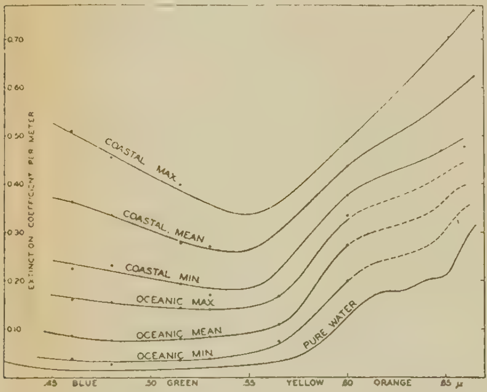

Fig. 13. Extinction coefficients of radiation of different wave-lengths in pure water and in different types of sea water. [From Sverdrup, Johnson, and Fleming, *The Oceans* (Prentice-Hall, Inc., New York).]

One serious limitation of the Secchi disk method of determining the proper camera distance arises when the water is stratified, since in this case information as to the transparency of the water near the surface is useless in considering photography of the bottom. This situation may be expected to occur in most shoal water in summer and to be particularly bad near estuaries. Some photographic evidence of it has been found, but no data from systematic surveys are available.

Another well-known method for estimating the transparency of sea water is that of lowering a photoelectric cell to various depths in daytime, and calculating the extinction coefficient, k, for the penetration of daylight. This is the fraction of light lost per meter increase in depth. Although k might be expected to vary independently of the Secchi disk reading, the available evidence (Poole and Atkins, 1929), (Clarke, 1941) supports the relation $k = 1.7/D$ when D is the Secchi disk reading in meters. This method shares with the Secchi disk the restriction to daytime and the vulnerability to stratification in the water, and has the added disadvantage that it requires more time and equipment.

Transparency meters, which can measure the amount of light transmitted between a standard source and a photoelectric cell, mounted on a frame at a suitable distance apart and protected against daylight, have been built by Petterssen (1936); and considerable work on such an instrument has also been carried out at Woods Hole.

Such meters can give the absolute transparency near bottom, or the relation of transparency between surface and bottom for the purpose of extrapolating Secchi disk readings, and are directly applicable to the problem at hand. They will become very useful if they are ever developed to the point where it is significantly less work to use them than to take and develop a test photograph.

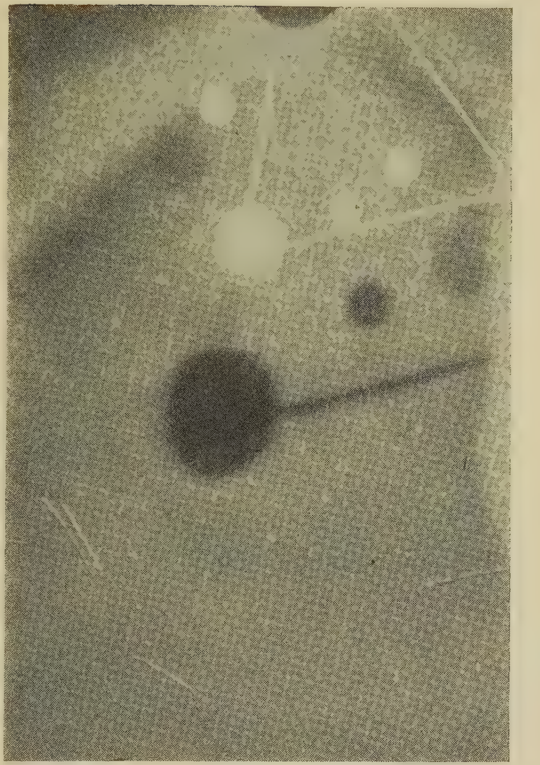

FIG. 14. Tubular organisms, tentatively identified as quillworm tubes. The triangular, white apparatus is a current meter attached to the camera. The white spheres have been variously weighted so that their relative deflection is a measure of current strength. Current direction is oriented by a compass (large disk in foreground) (C-66-a).

Approx. area covered: 2.4′×4.5′.
Position: Lat. 39° 35′ N, Long. 70° 57′ W.
Depth: 1950 (ft.).
Date: 7–16–40.
Secchi disk reading: —.
Shutter speed: 1/20.
Camera to bottom: 7 ft.
f stop: 4.5.
Light to bottom: 2 ft.
Focus: 8 ft.
Light source: No. 5 flash bulb.
Film: Panatomic X.

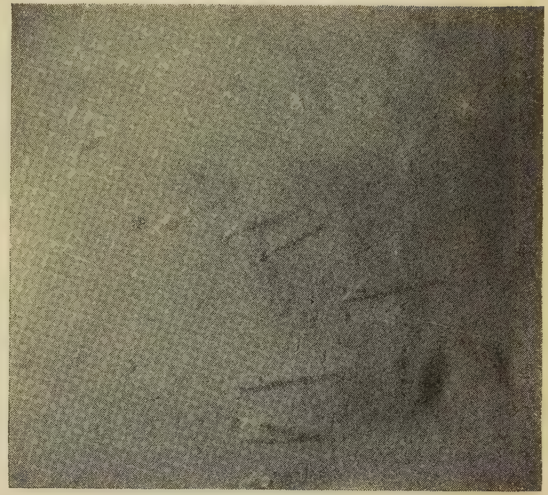

FIG. 15. Crab, hermit crab, starfish, and seapens, as well as various animal tracks and traces (C-76-9).

Approx. area covered: 4.3′×4.3′.
Position: Lat. 40° 19′ N, Long. 71° 22′ W.
Depth: 300 (ft.).
Date: 10-9-41.
Secchi disk reading: —.
Shutter speed: 1.
Camera to bottom: 7 ft.
f stop: 6.3.
Light to bottom: 2 ft.
Focus: 5¼ ft.
Light source: No. 5 flash bulb.
Film: Plus X.

3. Spectral Distribution

The absorption of different colors of light in sea water varies considerably, resulting in selective absorption. Measurements of this effect have been made by Utterback and Clarke in this country and by Poole and Atkins in England, as well as by many others.

Figure 13 shows the extinction coefficients of radiation of different wave-lengths in pure water and in different types of sea water as determined by Utterback. The general increase in the absportion coefficient of oceanic and coastal water over that for pure water is due to the presence of suspended particles that absorb radiation. Scattering from the suspended particles is much greater for the shorter wave-lengths than for the longer ones, as would be expected from Rayleigh's law that particles smaller than the wave-length scatter inversely proportional to the fourth power of the wave-length. The result of this scattering is to shift the wave-length of minimum absorption coefficient from the far blue for pure water to blue for oceanic waters, to green for coastal waters, and to yellowish green for very turbid coastal water.

V. UNDERWATER PHOTOGRAPHY AS A TOOL

1. Biological Studies

At moderate depths (to about 100 fathoms) underwater photography affords an excellent means of studying marine life, undisturbed and in its own environment. Besides many pictures of fish and other marine organisms, photographs taken on bottoms suitable for preserving tracks show the traces of various animals, which may give information about their habits and movements (see Fig. 15).

At great depths (to 3000 fathoms) photog-

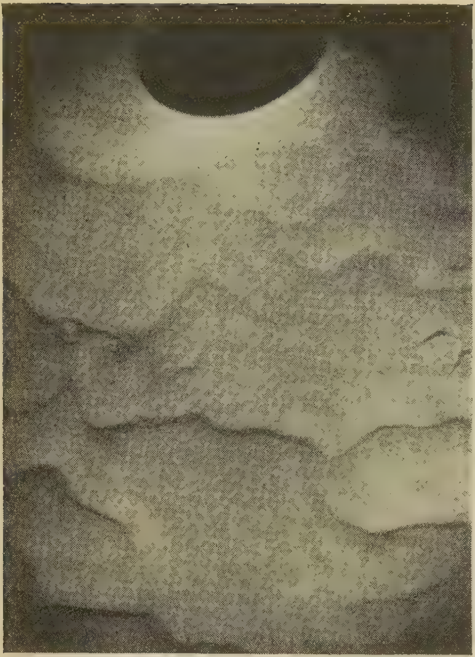

FIG. 16. Sand ripple photographed in the Gulf of Maine (C-35-b).

Approx. area covered: 2.4′×4.5′.
Position: Lat. 41° 20′ N, Long. 69° 04′ W.

Depth: 498 (ft.).	Date: 6–8–40.
Secchi disk reading: 12 ft.	Shutter speed: 1/20.
Camera to bottom: 7 ft.	f stop: 4.5.
Light to bottom: 2 ft.	Focus: 6 ft.
Light source: No. 5 flash bulb.	Film: Plus X.

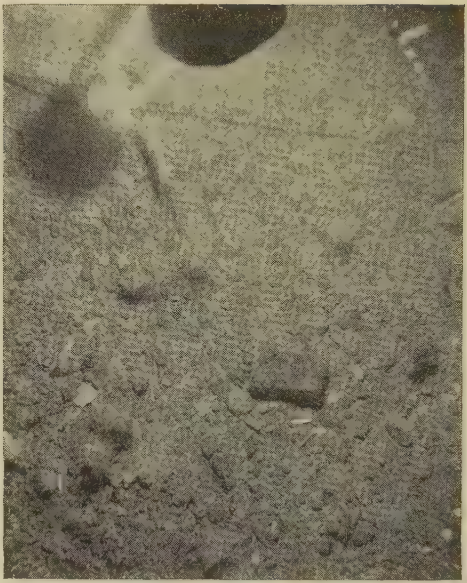

FIG. 17. View of the current meter, showing white pointer on current strength indicator in upper right-hand corner. The head of a fish, trapped beneath a trawler's line, shows at the right edge of the picture (C-48-a).

Approx. area covered: 2.4′×4.5′.
Position: Lat. 41° 34′ N, Long. 66° 24′ W.

Depth: 324 (ft.).	Date: 6–23–40.
Secchi disk reading: 32 ft.	Shutter speed: 1/20.
Camera to bottom: 7 ft.	f stop: 6.3.
Light to bottom: 2 ft.	Focus: 5 ft.
Light source: No. 5 flash bulb.	Film: Plus X.

raphy appears to be the only simple method of observing and taking a census of the population. Little is known about life at the bottom of the deep oceans because of the great difficulty of making observations and collecting data. Collecting nets cannot be towed rapidly at depths of several miles; thus only the slowest or weakest creatures are caught in them. Furthermore, deep sea animals, acclimated to life under great pressures, are seldom brought to the surface undamaged or alive. The observations made by Beebe in Barton's bathysphere at depths of 400 to 2240 feet are of value, but they involved an entire expedition, including elaborate equipment and a large staff; and they did not extend to or near the ocean bottom, as it was considered hazardous to risk grounding the bathysphere. The underwater camera supplies an instrument for observing and recording life on the deep ocean bottom, simple enough to be handled by one or two men from any sea going vessel.

A photographic investigation of the amount of light at the bottom of the deep ocean has been suggested. Many pelagic fish living in deep water (within 500 meters of bottom) where there is little or no solar light, have been found blind or with poorly developed eyesight, suggesting adaptation to life in darkness. However, bottom-living fish at great depths have been found with normal eyesight, pointing to some source of light in their environment. This is further supported by the fact that fresh water fish living in dark caves, where there is no biological source of light, are blind. Large numbers of luminescent organisms may be present on the bottom of the deep oceans; and this can be determined by a series of long exposures with a free floating camera, allowed to remain on the bottom for the required time.

Figures 14 and 15 are typical underwater photographs showing features of biological interest.

2. Geological Studies

A conventional bottom sampler, which picks up a small fraction of a square foot of the ocean bottom and tends to scramble it together, is fairly satisfactory on sand or mud bottoms, but inadequate if the bottom consists of boulders or ledges, or is patchy. The ideal instrument is a sampler combined with a camera to photograph the environment of each sample obtained.

Clearly defined sand ripples have been photographed in depths as great as 498 feet (see Fig. 16), but the limit of depth at which they occur has not been definitely established. Numerous patches of sandy bottom on Georges Bank have been photographed. The currents on Georges Bank are rotary, that is, their direction changes continuously through 360° during each tidal cycle of approximately 12 hours. In all of the photographs, the sand ripples have the orientation (at right angles to the current) which would be produced by the existing tidal currents. This proves that the sand in the localities investigated is continually shifted by the tidal currents, a fact of importance in all theories of the origin and structure of the continental shelf. Photography offers a direct method of determining whether or not bottom materials are being transported by currents in any particular case.

3. Oceanographic Studies

The widest future application of underwater photography to oceanographic work appears to be increasing the scope and flexibility of present measuring instruments by a photographic record of their readings. Figures 14 and 17 are records of current meters used in the study of current near bottom, mentioned above.

It has been proposed to measure the very feeble currents at the bottom of the deep oceans, which are thought to transport cold water from polar to equatorial regions, by taking successive photographs of a small cloud of dye released in the water, using a free floating camera resting on bottom.

4. Miscellaneous Studies

Submerged wrecks have been photographed very successfully by the use of automatic, suspended cameras. Much information as to the identity, position on the bottom, duration of submergence, and general condition of the wreck may be obtained without risking a diver (see Fig. 18). Salvage operations are facilitated when divers are used if they can bring back photographs to amplify their verbal reports. This is particularly true at great depths, where the excessive pressure interferes with the diver's mental processes. Wrecks have been successfully photographed in depths down to 330 feet.

Underwater photography offers a means of obtaining indisputable evidence about the condition of bridge footings, moorings, and other more intricate submarine installations.

VI. CONCLUSIONS

Methods of constructing and operating various types of automatic underwater cameras for all depths in the oceans are given. Small size and light weight are considered paramount features of design. Cameras are pointed downward, as subjects for underwater photography are more numerous on the ocean bottom than in the intermediate water. By screening the light source and placing it below the camera, as near as

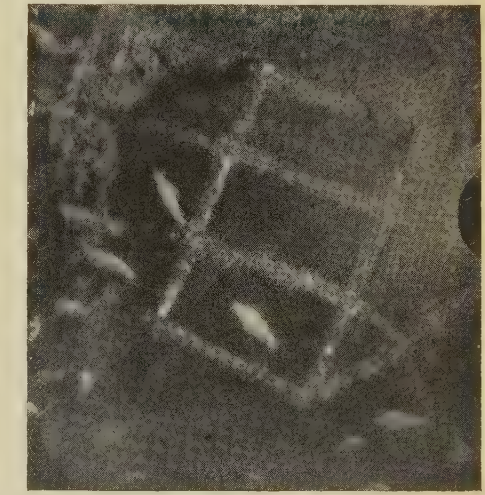

FIG. 18. Part of a sunken wreck, with a school of fish swimming through it (338-W-R).

Approx. area covered: 6.6′×6.6′.
Position: Lat. 34° 31′ N, Long. 76° 01′ W.
Depth: 138 (ft.). Date: 8–4–43.
Secchi disk reading: 30 ft. Shutter speed: 1/50.
Camera to bottom: 12 ft. f stop: 5.6.
Light to bottom: 7 ft. Focus: 9 ft.
Light source: No. 22 flash bulb. Film: Plus X.

possible to the bottom, scattering of light by water is minimized, and side lighting on the subject provided.

Methods of measuring transparency of sea water are evaluated from the viewpoint of underwater photography. Except for the Secchi disk, all methods tested are considered too cumbersome to be of value.

Submarine photography is an important tool in biological, geological, and oceanographic studies. Several hundred photographs have been used for the identification of wrecked ships and as aids in salvage operations, in depths down to 390 feet. More than 1000 clear pictures of the ocean bottom, in depths from 12 to 2400 feet, have been obtained.

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THE INFLUENCE OF TEXTURE AND COMPOSITION OF SURFACE ON THE ATTACHMENT OF SEDENTARY MARINE ORGANISMS *

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Marine installations of various kinds necessitate exposure of construction materials under sea water. Data dealing with the amount of fouling accumulated by such materials are not abundant. Information which might be of aid to the scientist seeking the most favorable material upon which to collect sedentary organisms for study is also scanty. The present study was undertaken to determine the effect

Table I

Effect of surface texture of glass on attachment of sedentary organisms. (Numbers of individuals on each surface of 80 square inches of plate)

Surface number	Plain 0	Sand-blasted 1	Factrolite 2	Prestlite 3	Ribbed 4	Pentecor 5
Series No. 1, Tahiti Beach[1] 39 days (8/22/42–9/30/42)						
Hydroides sp.	143	265	152	506	349	197
Spirorbis sp.	85	188	122	90	163	110
Barnacles	1,948	1,072	1,162	975	1,674	2,140
Total	2,176	1,525	1,436	1,571	2,186	2,447
Average pop.	725.3	508.3	478.7	523.7	728.7	815.7
Average/square inch	9.1	6.4	6.0	6.5	9.1	10.2
Series No. 2, Miami Beach[2] 17 days (8/22/42–9/8/42)						
Wet weight (grams)	51.0	45.5	50.0	41.0	50.0	41.0
Dry weight (grams)	8.5	6.4	7.9	5.5	7.5	8.8
Barnacles	308	227	268	213	263	331
Series No. 3, Miami Beach[2] 30 days (9/15/42–10/15/42)						
Wet weight (grams)	164.5	174.0	149.0	150.0	126.0	155.5
Dry weight (grams)	51.5	50.0	30.0	24.0	24.0	33.0
Barnacles	642	515	554	778	798	977

[1] Subtropical testing service.

[2] Beach boat slips.

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* The observations described here were made while the authors were engaged by the Woods Hole Oceanographic Institution in an investigation of fouling, under contract with the Bureau of Ships, Navy Department, which has given permission for their publication. The opinions presented here are those of the authors and do not necessarily reflect the official opinion of the Navy Department or the naval service at large. Contribution No. 349 from the Woods Hole Oceanographic Institution.

of surface irregularities and of substrate composition on the establishment of sessile populations. The experiments were conducted in Biscayne Bay at Miami, Florida, where subtropical conditions favor the attachment of fouling organisms throughout the year.

Grateful acknowledgment is made to Dr. A. C. Redfield and Dr. F. G. Walton Smith for many helpful suggestions.

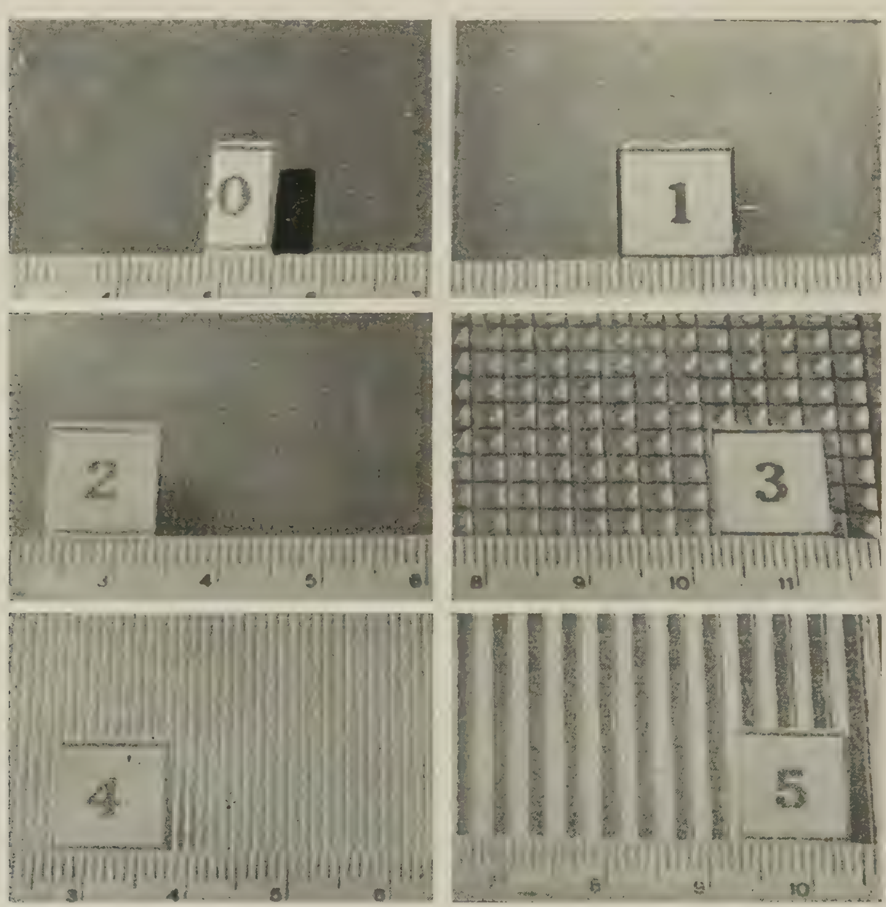

Figure 1. Glass surfaces used in testing the relation of surface irregularities to fouling. 0. Plain. 1. Sandblasted. 2. Factrolite. 3. Prestlite. 4. Ribbed. 5. Pentecor.

Effect of Surface Irregularity

Commercial glasses, manufactured by the Pittsburgh Glass Company, with various surface irregularities were used for this study. Six 8 × 10 inch glass plates were assembled, irregular surface down, in a rack suitable for floating on the surface of the water. The floats were constructed in such a way that sea water could move freely on both sides of the exposed surface. The backs of the panels which were all relatively smooth were placed upward. The fouling on the back surfaces was not recorded. The surface irregularities of the panels are shown in Figure 1 and may be described as follows:

Surface Number:

0. *Plain*	Smooth glass, polished.
1. *Sandblasted*	Glass sandblasted on lower side.
2. *Factrolite*	Surface consisted of pyramidal depressions of which there were about 144 per square centimeter.
3. *Prestlite*	Approximately nine pyramidal depressions per square centimeter.
4. *Ribbed*	Surface of V-shaped grooves, nine grooves per centimeter of width.
5. *Pentecor*	Approximately three V-shaped grooves per centimeter of width.

Results obtained from three series of experiments in which the glass surfaces were exposed are shown in Table I.

The Sessile populations which grew on the glass plates were composed primarily of barnacles and tubeworms, with irregular, perhaps seasonal, appearances of tunicates and *Anomia* sp. Barnacles (*B. improvisus* and *B. amphitrite niveus* in order of relative abundance) were numerous in both locations, but those at Tahiti Beach were always very small compared to those at Miami Beach. Many more barnacles attached to the lower (shaded) surfaces of the panels than to the upper surfaces where light was more abundant. This is in agreement with the experience of Pomerat and Reiner (1942), who report that larger numbers of barnacles accumulate on dark surfaces than on light surfaces. The shaded undersides of the glass panels, being darker than the upper sides, appear to attract more cyprids and hence show a greater barnacle accumulation.

The various surface textures of glass had little influence on the number of attached organisms. In these experiments barnacles were consistently slightly more numerous on Pentecor than on smooth glass. This behavior was confirmed in the experiment reported in the following section although conditions of exposure were not exactly parallel. In the first experiment the glass panels were floated at the surface in a shaded location, while in the second they hung vertically below low tide

Table II

Influence of substrate on fouling, sixty days' exposure at the beach boat slips, September 25, 1942–November 25, 1942

Substrate	Weight of fouling on panel area of 264 sq. in., that of wood panels employed	
	Wet weight grams	Dry wt. grams
1. Dade County pine	675.1	346.5
2. Gum	1127.6	531.4
3. Magnolia	1165.4	446.4
4. White pine	968.7	446.8
5. Cypress	954.8	392.0
6. Tile	980.1*	487.3
7. Cement	1033.0*	534.1
8. Glass	386.1	167.3

* Corrected to an area, 264 sq. in., equal to that of the wood panels.

under sun exposure. Counts of tubeworms were made on only one set of exposures. *Hydroides* sp. was most abundant on Prestlite and *Spirorbis* sp. was most abundant on sandblasted glass.

COMPOSITION OF THE SURFACE

Unpainted panels of wood of five species, clay roofing tiles, cement roofing plates, and a glass panel were exposed for 60 days at the Beach Boat Slips in Miami Beach.

TABLE III

Effect of substrate on fouling, exposures of three months at South Dock, "Belle Isle," Miami Beach, Florida, January 9, 1943–April 9, 1943, all materials applied to, or mounted on, wood unless otherwise noted

Composition of surfaces	Wet weight* (grams)	Dry weight* (grams)	Number* of barnacles	Notes
Plastics				
1. Celluloid	3.8	2.2	11	Thin coat of algae.
2. Plasticel	24.3	12.2	124	Barnacles' bases easily removed.
3. Lucite	5.6	1.7	41	
4. Formica	6.9	3.2	11	
5. Isobutyl Methacrylate	15.4	7.2	70	Film applied to glass panel. Plastic peels intact with barnacles.
Glass				
6. Prestlite	57.0	25.2	176	Some barnacles 12 mm. across.
7. Pentecor	46.0	25.0	148	Some barnacles 12 mm. across.
8. Sandblasted	23.6	7.0	46	6 calcareous tubeworms; tunicates.
9. Smooth	4.5	1.7	16	Green slime may have caused fish to remove young barnacles.
*Paints and ingredients***				
Coatings applied to steel panels				
10. Ester gum vehicle	36.3	8.1	58	Tunicates and bryozoa.
11. Rosin vehicle	2.7	0.4	0	Fish spawn both sides.
12. Anticorrosive paint 42-A	2.7	0.5	9	Baracles very small.
13. Vehicle of 15RC	6.1	3.3	43	
14. Antifouling paint 7C	0.0	0.0	0	Some slime film.
15. Antifouling paint 8C	0.6	0.3	14	Small barnacles close to edge.
Coatings Applied to Wood				
16. Ceraloid	57.6	38.5	183	
17. Paraffin	11.3	6.1	59	Lomnoria active in breaking paraffin.
18. Asphaltum	121.4	34.3	768	Barnacles only.
19. Asphaltum varnish	67.8	13.8	256	Some bryozoa.
20. Spar varnish	45.1	7.0	304	
21. Navy grey	41.6	5.6	150	Algae.
22. Anti-corrosive 42-A	48.2	10.7	156	

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* Corrected to an area of 144 square inches.

** Anticorrosive 42A is a standard Navy formula. Vehicle of 15RC is the non-pigmented portion of a standard Navy antifouling paint. Antifouling paints 7C and 8C are experimental modifications of a standard Navy antifouling paint of the cold plastic type in which the toxic pigment is reduced to 50 and 60 percent of the normal value.

TABLE III—*Continued*

Composition of surfaces	Wet weight* (grams)	Dry weight* (grams)	Number* of barnacles	Notes
Woods				
23. Dade County pine (soaked 60 days)	395.2	120.7	748	Bryozoa.
24. Gum (soaked 60 days)	452.1	133.4	686	
25. Dade County pine (unsoaked)	144.3	27.3	125	Hydrozoa, bryozoa.
26. Gum (unsoaked)	249.8	43.5	222	
27. Soft pine	57.6	11.5	184	
28. Teak	143.8	88.7	306	Large barnacles.
29. Maderia	173.7	84.2	358	Many fish eggs.
30. Greenheart	77.0	40.8	342	
31. Balsa	2.9	1.6	5	Wood very soft.
Metals				
32. Steel	224.4	42.8	88	
33. Galvanized iron	2.6	0.7	6	Barnacles easily removed.
34. Zinc	1.0	0.2	0	Active corrosion.
35. Lead	30.6	50.9	396	Large barnacles.
36. Monel	1.6	0.5	6	Many fish eggs.
37. Nickel	43.2	10.7	126	
38. Galvanized iron pipe	4.7	3.0	27	Barnacle on rusted threads and damaged edges.
Miscellaneous				
39. Linoleum	79.7	23.0	193	
40. Deck canvas no. 10	5.1	2.3	7	Sagging-algae eaten by fish.
41. Sole leather	32.4	12.4	66	
42. Masonite, heat tempered	138.6	31.8	594	Brown tunicates.
43. Asbestos	284.2	65.9	980	Bryozoa, *Anomia*, hydrozoa, calcareous tubeworm.

All panels were suspended in a vertical position approximately two feet beneath the mean low water mark. The site was well shaded by a protecting roof. The results obtained are presented in Table II.

The weights of the populations (barnacles, tubeworms, tunicates, bryozoa, and algae) which accumulated on the woods, tile, and cement were of the same order of magnitude, though variations as great as 59 per cent were observed. The weight of organisms accumulated on glass was approximately 30 per cent of that collected from other substrate materials.

A much larger number of materials were tested in a second experiment, the results of which are given in Table III. Exposure was made for three months at South Dock, Belle Isle, in Miami Beach, where conditions of bright sunlight, active current movement, and moderate fouling incidence were found. Growth on the panels consisted primarily of barnacles (*B. improvisus* and *B. amphitrite niveus*) with occasional tufts of hydrozoa and patches of colonial tunicates. A blanket of algae having very short filaments grew on panels of light color or shaded background. Large sets of fish eggs were found on the rosin vehicle and Monel. Borings of *Limnoria* sp. were everywhere evident in unprotected wood.

The substrates accumulating heaviest populations were asbestos, asphaltum, Dade County pine (pre-soaked 60 days), gum wood (pre-soaked 60 days) and Masonite. Asbestos shingle, commonly used as clapboarding, yielded the richest harvest as measured by the number of barnacles. A comparison of asbestos and Masonite, two of the best collectors, is shown in Figure 2. The asphaltum used was of the type employed as aquarium cement. It accumulated barnacles only.

Panels of gum and Dade County pine, which had been exposed for 60 days in the earlier test reported in Table II, were included for comparison with unsoaked specimens of these woods. The unsoaked woods developed much less fouling.

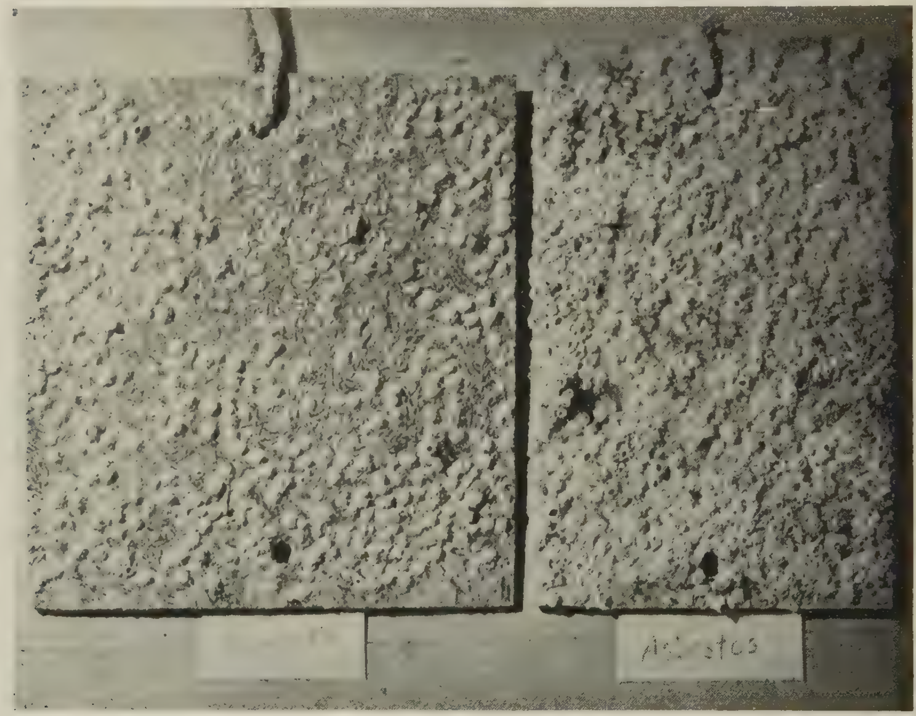

FIGURE 2. Accumulation of fouling organisms on masonite and asbestos after 90 days' exposure at Belle Isle, Miami Beach, Florida.

Intact galvanizing on iron was very resistant to marine life. No barnacles were obtained on zinc, on the experimental antifouling paint 7C or on rosin vehicle, a common paint component.

Materials with hard non-porous and non-fibrous surfaces were in general rather poor collectors of fouling. The best accumulation of sedentary populations was found on surfaces which were porous and/or fibrous. Surface of paints, paint ingredients and linoleum are in general non-porous and non-fibrous. Compared to the size and strength of the barnacle cyprid they are also smooth and hard. The histogram (Fig. 3) summarizes the collective efficiency of the substrates.

Some results were undoubtedly spurious, and these should be noted. Fouling on the antifouling paint 8C which occurred along the edges of the panel was probably

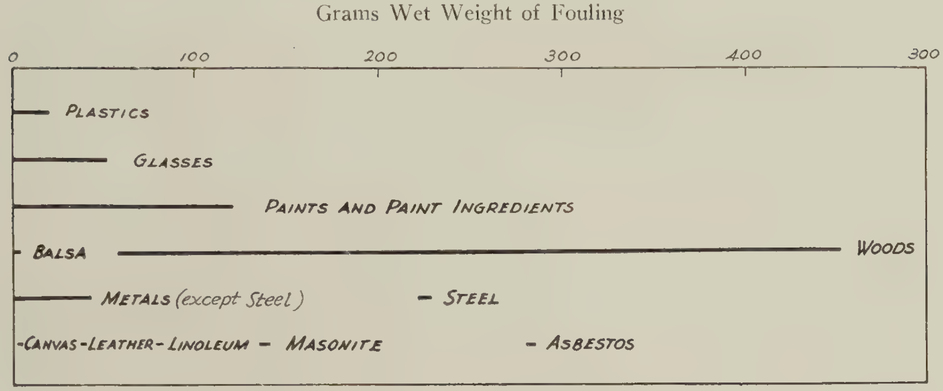

FIGURE 3. Relative amounts of fouling on various classes of materials used as test panels.

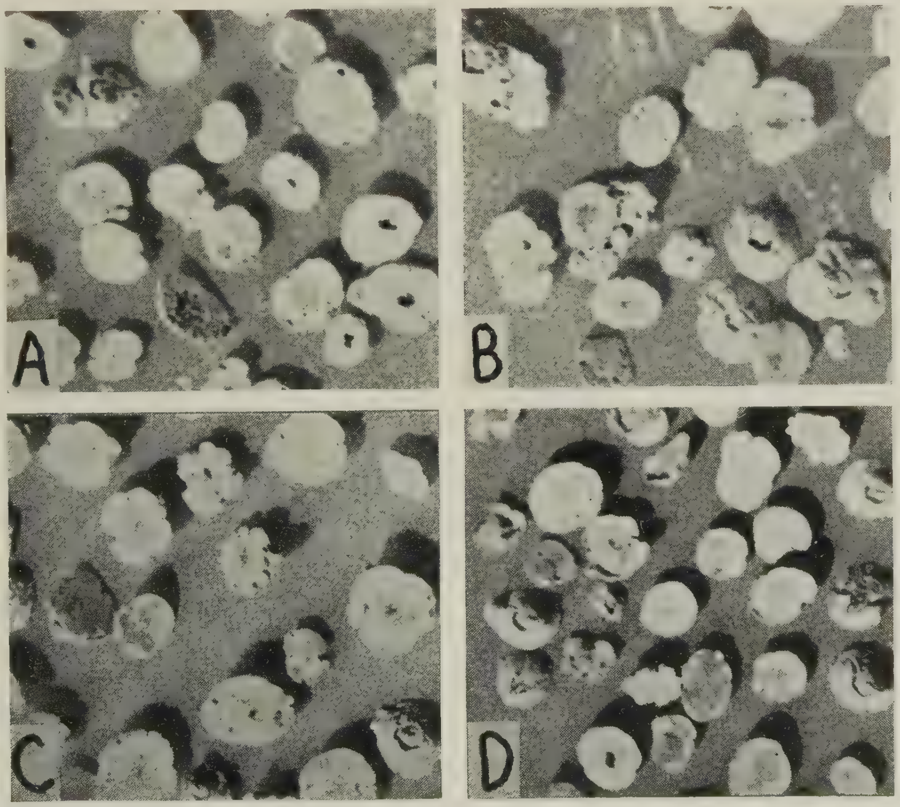

FIGURE 4. Bases of barnacles grown on various substrates. A. Navy grey. B. Antifouling paint 15RC. C. Ester gum. D. Anticorrosive paint 42A.

due to imperfections of the paint surface. In contrast, 7C which contained less copper was not fouled. Deck canvas and smooth glass both supported a culture of green algae which evidently served as food for fish. Active feeding on these panels unquestionably disturbed other fouling organisms. Balsa wood was apparently sloughing its surface and thus loosening attached forms. In spite of these minor qualifications, the results involve a range of population numbers sufficiently wide to indicate the relative merits of the substrates used.

One of the most interesting of the results was observed when barnacles were removed from the various substrates. Some of the substrates bore barnacles with deeply scalloped margins (Fig. 4) instead of the typical smooth edges. These margins suggested that localized irregular marginal growth interruptions had taken place. Such barnacles were collected from:

Spar varnish
Linoleum
Navy grey topside paint (P–50)
Antifouling paint vehicle 15RC
Ester gum paint vehicle
Anticorrosive paint 42–A

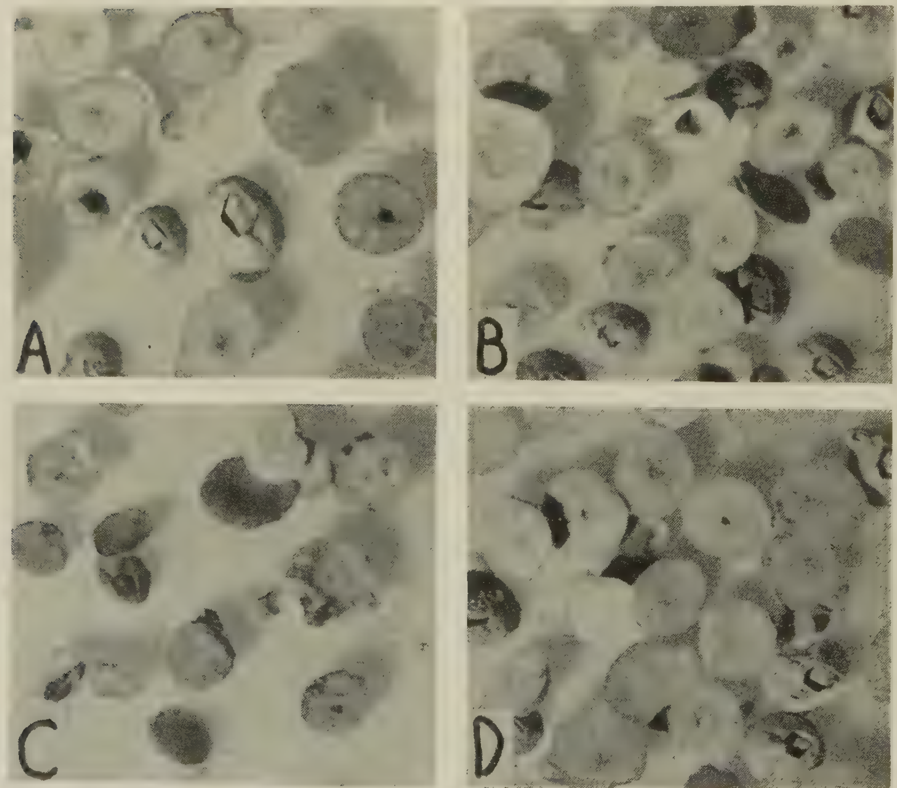

FIGURE 5. Bases of barnacles grown on various substrates. A. Isobutyl methacrylate. B. Plasticel. C. Soft paraffin. D. Ceraloid.

Barnacles growing on soft paraffin had distinctly concave bases. Mosaics of bases with angular margins were typical of barnacles attached to lead but were also found on other overcrowded substrates. It was possible to remove barnacles with intact bases very easily from several materials, including plasticel, ceraloid, and isobutyl methacrylate (Fig. 5). This finding might prove useful in designing experiments in which the minute anatomy of basal structures was to be studied.

SUMMARY

1. Submerged samples of 40 different construction materials were used as substrates for the collection of sedentary populations. The barnacle counts in the populations ranged from 980 on asbestos shingles to zero on zinc and on two paint coatings, after three months' immersion in Biscayne Bay at Miami Beach, Florida.
2. Various surface textures of glass plates were found to exert no significant influence on the accumulation and growth of sedentary marine organisms, although smooth clear glass accumulated smaller populations in the comparatively short exposure periods, 1–3 months .
3. The results suggest that efficiency of a substrate as a fouling collector is in general correlated with porosity of surface or with fibrous nature of surface. Smooth, non-porous, non-fibrous surfaces, especially if also hard, seem to be poor accumulators of sedentary organisms.
4. Further testing of substrates is greatly to be desired in this connection.

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Contribution No. 350

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 16, NO. 2, PP. 43–51
FIGS. 1–3, TABLES 1–3, AUGUST, 1946

A STUDY OF TEXTURAL CHANGES IN A BEACH BY REPEATED SAMPLINGS*

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ABSTRACT

Mechanical analyses of repeated samplings of Ipswich Beach, Massachusetts, covering an eleven month period are presented. The successive samplings indicate that a change in the median diameter at one station is nearly always paralleled by a change in the same direction at the other stations. At an individual station the spread between high and low tide medians tends to remain of the same order. To a much lesser degree, the skewness and sorting values tend to change in unison. On a comparable beach, a single sampling should give the same range of difference in successive medians along the beach and thus indicate the median trend.

INTRODUCTION

In the usual textural study of the beach environment limitations of time prevent the collecting and mechanical analysis of more than one or two sets of samples. Also the scope of the investigation may prevent sampling of the whole beach unit on a single tide, so that samples taken on different days must be grouped together and evaluated as a continuous whole. The question inevitably arises, whether all samples are taken on the same day and tide or not;—would subsequent re-sampling give approximately the same difference between successive samples and exhibit the same trends? As part of a general study of certain New England beaches the problem was investigated by repeating a series of three stations six times. Each station consisted of low and high tide samples. Two of the stations were given seven samplings. Intervals between samplings varied from slightly less than one month to over two months. The first samples were taken October 8, 1932, the last on September 4, 1933.

As a background for the repeated stations, a series of samples extending from the mouth of the Merrimac River at Plum Island southwards to Coffins Beach was collected in the fall of 1932 and the spring of 1933.

The writer wishes to acknowledge his indebtedness to Prof. P. E. Raymond and to H. C. Stetson for their interest in the problem and invaluable assistance in the collection of the samples.

DESCRIPTION OF AREA

The general area with the positions of the repeated stations marked "A," "B" and "C" is shown by Figure 1. Between Coffins Beach and the inlet separating it from Ipswich Beach the shore is composed of granite. Otherwise the entire stretch from the northerly end of the area to Coffins Beach is sandy. At the southern end of Plum Island a cliff about 10 feet above high tide and numerous boulders on the beach mark the landward remnant of a drumlin. Across the inlet at Ipswich and immediately to landward of Station "A," there is a well developed sea cliff in a large drumlin. The vegetation indicates that little or no cutting was in progress at the time of the study. With these exceptions the beach is bordered by low dunes. Back from the shore there are dunes as high as 30 feet on Plum Island, 60 feet at Ipswich, and 80 feet at Coffins Beach.

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* Contribution No. 350, Woods Hole Oceanographic Institution.

A sample from each division is recorded in Figure 2 below.

The beach at the northern limit of the sampling is narrow, measuring 75 feet from the dune line to the low water mark, with slopes of 6 to 8 degrees. On Ipswich Beach the width has increased to nearly 500 feet with slopes slightly over 2 degrees. Coffins Beach has gentle slopes comparable to those at Ipswich.

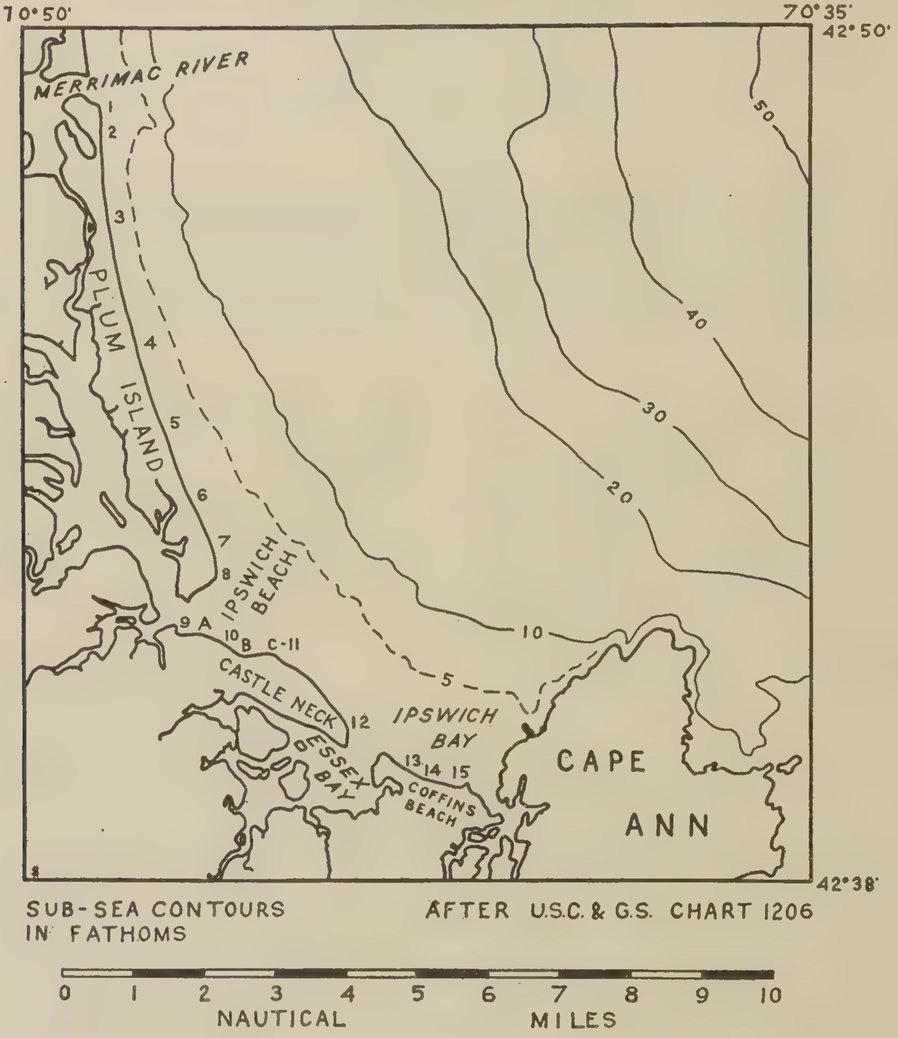
70°50'
70°35'
42°50'
42°38'
MERRIMAC RIVER
PLUM ISLAND
IPSWICH BEACH
CASTLE NECK
ESSEX BAY
IPSWICH BAY
COFFINS BEACH
CAPE ANN
1
2
3
4
5
6
7
8
9 A
10 B
C-11
12
13
14
15
5
10
20
30
40
50
SUB-SEA CONTOURS IN FATHOMS
AFTER U.S.C. & G.S. CHART 1206
0 1 2 3 4 5 6 7 8 9 10
NAUTICAL MILES

FIG. 1.—Portion of Massachusetts coast showing location of beach samples.

Height of tide for the region is about 8 feet.

The Coast and Geodetic Survey charts for the region show a shallow foreshore off Plum Island which continues southward to Coffins Beach. One and two foot shoals (mean low water) are indicated off Ipswich and 5 and 6 foot spots off Plum Island and Coffins Beach. The shoal water is indicated by breaking waves even with a moderate swell coming in. The ten fathom line is a mile offshore at the north end of Plum Island and two miles off Coffins Beach.

Tidal scour has made, or preserved, depths of 30 to 40 feet in the inlet behind Plum Island and depths greater than 20 feet in the channel in Essex Bay. Since these depths are found only where the channels are narrow, it appears that the tidal currents are not of importance as scouring agents in the open sea.

From examination of Figure 1, the location chart, one would infer that the Castle Neck end of Ipswich Beach had been built southeastward from the drumlin which is nearly opposite the southern end of Plum Island. Beyond the drumlin a succession of foredune ridges parallel the shore. Inland they are masked by higher and irregular dunes. Especially towards the end of the neck these dune ridges curve gently into the south away from the present beach. Thus a southeasterly growth is indicated for the beach as a whole. Bryan and Nichols (1) have found glacial till underlying some of these higher dunes. In spite of the fact that the neck is thus not entirely the result of wave and wind action, the evidence cited is believed sufficient to establish southeasterly drift for the shore materials. On Plum Island and Coffins Beach such conclusive evidence is not available, but their general appearance does not contradict the conclusion that the net transfer of material by shore processes is in a southerly to southeasterly direction.

Figure 1 indicates that the beach is exposed to northeasterly storms, the most violent experienced in the region. Cape Ann shelters the southern part of it from easterly storms. During southeasterly storms the entire beach is within the lee of Cape Ann.

The estuarine conditions of the Merrimac and other rivers in the vicinity rules them out as suppliers of new material to the beaches at the present time. In combination with this fact the almost entire absence of cliff cutting means that the beach is receiving essentially no new material from the land at the present time, with the single exception of loss entailed by the foredunes during storms accompanied by excessively high water. The original supply of material must date back to the close of glacial time.

LABORATORY PROCEDURE

Samples were collected by scooping up 300 to 400 grams of sand a few feet below the swash marks of the last high tide, and at the waters edge. Collecting was done at the reported time of low tide for the area.

In the laboratory the sand samples were washed free of salt, dried and quartered down to approximately 50 grams. They were then sieved for ten minutes on a mechanical shaker using screens of the Wentworth grade scale, openings 2.0, 1.0, 0.5, 0.25, 0.125 and 0.062 mm. The resulting size fractions were weighed, percentages calculated and cumulative curves constructed. From these curves the first and third quartiles and the median were read. Following Trask (2), the coefficient of sorting, $\sqrt{Q1/Q3}$ and the log skewness, $\log(Q1 \times Q3)/M^2$ where Q1 and Q3 are the first and third quartiles, respectively, and M the median, were calculated.

MECHANICAL ANALYSES—PLUM ISLAND TO COFFINS BEACH

In Figure 2 the median diameter and coefficients of sorting and skewness for the samples have been plotted against distance along the beach, from the mouth of the Merrimac River to Coffins Beach. At the northerly end of the series the high tide median is about 0.70 mm. Toward the southerly end of Plum Island the median decreases rapidly, reaching a value of 0.21 mm. at the last station at which a high tide sample was taken. The decrease at low tide is somewhat more regular. The largest value, at the mouth of the Merrimac, exceeds 1.0 mm., the smallest, at the extreme southern end, is less than 0.2 mm.

Improvement in sorting parallels the

TABLE 1. *Plum Island-Ipswich-Coffins Beach*

Station Number	Q1	M	Q3	*So*	log *Sk*
High Tide Millimeters					
1a	.86	.69	.53	1.28	−.02
2a	.81	.64	.45	1.34	−.04
3a	.72	.53	.39	1.35	.00
4a	.89	.71	.36	1.30	−.03
5a	.67	.52	.38	1.33	−.03
6a	.85	.62	.41	1.45	−.04
7a	.47	.39	.32	1.22	−.01
9a	.49	.37	.25	1.41	−.05
10a	.36	.27	.19	1.38	−.03
11a	.33	.26	.21	1.25	.01
12a	.25	.21	.17	1.23	−.02
Low Tide					
1b	1.82	1.05	.74	1.57	.09
2b	.74	.59	.42	1.34	−.04
3b	.90	.71	.52	1.32	−.03
4b	.63	.48	.36	1.32	−.01
5b	.65	.50	.37	1.32	−.02
6b	.48	.35	.25	1.38	.00
7b	.41	.32	.24	1.29	−.02
8b	.42	.33	.25	1.30	−.01
9b	.32	.23	.18	1.34	.04
10b	.50	.34	.23	1.47	.00
11b	.33	.24	.18	1.35	.01
12b	.30	.23	.18	1.31	.00
13b	.25	.21	.17	1.22	−.02
14b	.23	.19	.16	1.19	−.02
15b	.23	.19	.16	1.19	−.02
Dune					
5c	.40	.33	.25	1.28	−.03
10c	.28	.22	.18	1.26	.00
15c	.22	.19	.16	1.18	−.01

decrease in median, but no trend is evident in the skewness values. The prevailing negative values indicate that the mode, or peak of the frequency curve, is on the coarse side of the median. The decreasing medians are believed to be the result of selective longshore transportation of the finer grains along each beach section. These finer grains are able to remain on the beach to leeward because the environment becomes increasingly moderate to the south and east due to the protection afforded by Cape Ann. Sand is presumably carried from segment to segment via overlapping underwater spits. On one visit to Ipswich the swash marks between mid and high tide were marked by scattered coarse red stained quartz grains. These large red grains appeared identical with the red grains on Plum Island. The finer sand normal to Ipswich is mainly white quartz and free from stain.

TABLE 2. *Ipswich—Repeated Stations, 1932–1933. High tide samples precede low tide at each date*

	Q1	M	Q3	*So*	log *Sk*
Millimeters					
Station A					
Oct. 8	.34	.27	.21	1.27	−.01
	.45	.28	.21	1.47	.08
Jan. 5	.32	.24	.18	1.33	.00
	.47	.36	.25	1.37	−.04
Feb. 1	.28	.19	.16	1.32	.09
	.38	.28	.22	1.31	.03
Mar. 18	.36	.28	.21	1.31	−.01
	.44	.34	.25	1.33	−.02
May 1	.35	.22	.17	1.44	.09
	.39	.32	.23	1.30	−.06
June 18	.40	.33	.24	1.29	−.05
	.40	.31	.22	1.35	−.04
Sept. 4	.39	.28	.20	1.40	.00
	.41	.31	.22	1.36	−.03
Station B					
Jan. 5	.36	.27	.19	1.38	−.03
	.50	.34	.23	1.47	.00
Feb. 1	.32	.24	.18	1.33	.00
	.41	.37	.22	1.37	−.03
Mar. 18	.35	.26	.20	1.32	.02
	.44	.30	.23	1.38	.05
May 1	.31	.26	.20	1.25	−.04
	.52	.35	.26	1.42	.04
June 18	.35	.27	.20	1.32	−.02
	.61	.43	.27	1.50	−.05
Sept. 4	.35	.23	.18	1.40	.09
	.42	.34	.25	1.28	−.03
Station C					
Oct. 8	.33	.26	.21	1.25	.01
	.33	.24	.18	1.35	.01
Jan. 5	.43	.34	.26	1.29	−.01
	.55	.37	.28	1.40	.05
Feb. 1	.35	.24	.18	1.39	.04
	.36	.22	.18	1.41	.13
Mar. 18	.34	.24	.18	1.37	.03
	.37	.28	.21	1.33	.00
May 1	.33	.25	.18	1.35	−.02
	.37	.30	.22	1.30	−.04
June 18	.38	.30	.23	1.29	−.01
	.41	.33	.23	1.34	−.06
Sept. 4	.42	.30	.22	1.38	.00
	.40	.30	.22	1.35	−.01

The decrease in median values in the direction of drift is comparable with cases described by Pettijohn and Ridge (3) for a short beach in Lake Erie, and by the Beach Erosion Board (4) and MacCarthy (5) for certain sections of the Atlantic Coast between Long Island and Chesapeake Bay.

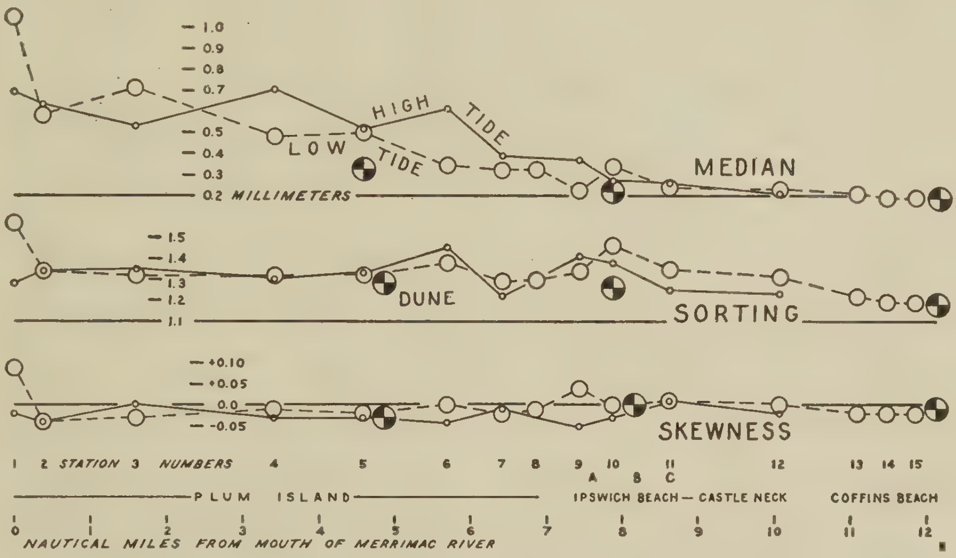

FIG. 2.—Median diameter, and coefficients of sorting and skewness plotted against distance, Plum Island to Coffins Beach.

On the plot against distance, Figure 2, samples from dunes backing each segment of the beach have been shown. As would be expected since the beach is the source of the sand, the median decreases and the sorting improves, in the direction of beach drift. Microscopic examination reveals no difference in angularity of grains of comparable sizes at the three stations.

CHANGES AT INDIVIDUAL STATIONS

The medians, quartiles and coefficients of sorting and skewness of the 40 samples comprising the repeated group are presented in Table 2. In Table 3 the data are condensed by listing the maximum average and minimum values for the median, sorting and skewness. However, the graph resulting from plotting the median, sorting and skewness against time in Figure 3 portrays the data in what is probably the clearest manner for discussion. It is to be noted that the ordinate scale is large in relation to the time or abcissa to separate, insofar as possible, small differences in the plotted points.

Station A.—In following through the medians for Station A it is seen that the high tide median is smaller than the low except on June 18 when the high tide reached its maximum, 0.33 mm. In spite of this exception there is a definite parallelism between the high and low plots. The average difference between high and low tide medians for the same date is 0.06 mm.

At three out of the seven sampling dates the high tide sorting is poorer than at low tide. This lack of any regular difference indicates that the particular environment at this station does not always produce a markedly better sorting at high tide than at low.

The skewness likewise is irregular with the high tide showing changes, especially in February and May, which are not reflected in the low tide value. It may be noted that in both months the medians retained an average spread with the low tide substantially coarser.

TABLE 3. *Ipswich—Repeated Stations. Maximum, Average and Minimum Values*

	Station	Median			Sorting			log Skewness		
		Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	Min.
		Millimeters								
High Tide	A	.33	.26	.19	1.44	1.34	1.27	.09	.02	−.05
Low Tide		.36	.33	.28	1.47	1.36	1.31	.08	−.01	−.06
High Tide	B	.27	.26	.23	1.40	1.33	1.25	.09	.00	.04
		.43	.36	.30	1.50	1.40	1.28	.05	.00	−.05
High Tide	C	.34	.28	.24	1.39	1.33	1.25	.04	.01	−.02
Low Tide		.37	.29	.22	1.41	1.35	1.30	.13	.01	−.06

Station B.—Values for this station begin in January. The high tide median is remarkably uniform with maximum value of 0.27 and minimum of 0.23 mm. At all sampling dates the low tide median is coarser, the graphs showing well marked parallelism. The curve for the sorting shows that up to the last sampling the low tide sampling has the poorer value. The worst sorting at low tide coincides with the maximum median (June).

Although the skewness curves cross each other twice, the high and low tide stay much closer to each other than do the corresponding curves at Station A. It thus appears entirely justifiable to state that a parallelism of trend is indicated.

Station C.—At this station the median curves show a distinct parallelism. With a variation in median from 0.24 to 0.34 mm. at high tide and from 0.22 to 0.37 mm. at low tide, the greatest spread between high and low tide is 0.05 mm. (high tide 0.25, low 0.30 mm., May 1). It is to be noted that at one sampling the high tide median equals the low and that at two other times it is 0.02 mm. smaller than the low.

The plot for the sorting likewise indicates some parallelism with time. Unlike Station B, however, the sorting is not always poorer at low tide, being from .03 to .05 better than high at three of the sampling dates.

The skewness shows a parallel plot with the low tide first showing positive values then "crossing" to the negative side of the high tide curve.

At individual stations one may therefore conclude that on the basis of the median curve, and to a lesser extent the skewness and sorting curves, if conditions change between samplings, both high and low tide samples tend to change in the same direction.

COMPARISON WITH TIME

Median—How well a change from sampling date to sampling date at one station is reflected in changes at the other stations is similarly shown by the curves as a whole. In the plot for the medians the tendency to "swing" together is well shown. Between the first and second samplings three of the four available values all increase. Between the January and the February samplings five samples show a decrease. This marked decrease in median is presumably due to the heavy winter storm which occurred a few days previous to the collection of the samples. The extreme high tide allowed the waves to cut into the shore dunes, thus furnishing the beach with a plentiful supply of finer material. The

March sampling shows a general increase, and May a decrease. June shows an increase and the final sampling either a general decrease or a steady situation.

Comparison of the different sorting curves indicates that just as at individual stations there is more variation between successive sorting values, than between successive median values, there is less parallelism evident than was the case with the median curves. There are nevertheless definite changes in the same direction, with only one to two samples failing to follow the general trend. Examples are the increase in 3 of the 4 samples between October and January, the crowding of the plotted points at the February and March dates, and the trend for May–June followed by all except Station A, high, and Station B, low. From June to September Station B, low is the only curve that fails to follow the grouping. It should, therefore, be safe to conclude that there is definite tendency for the sortings to change in the same direction with successive samplings.

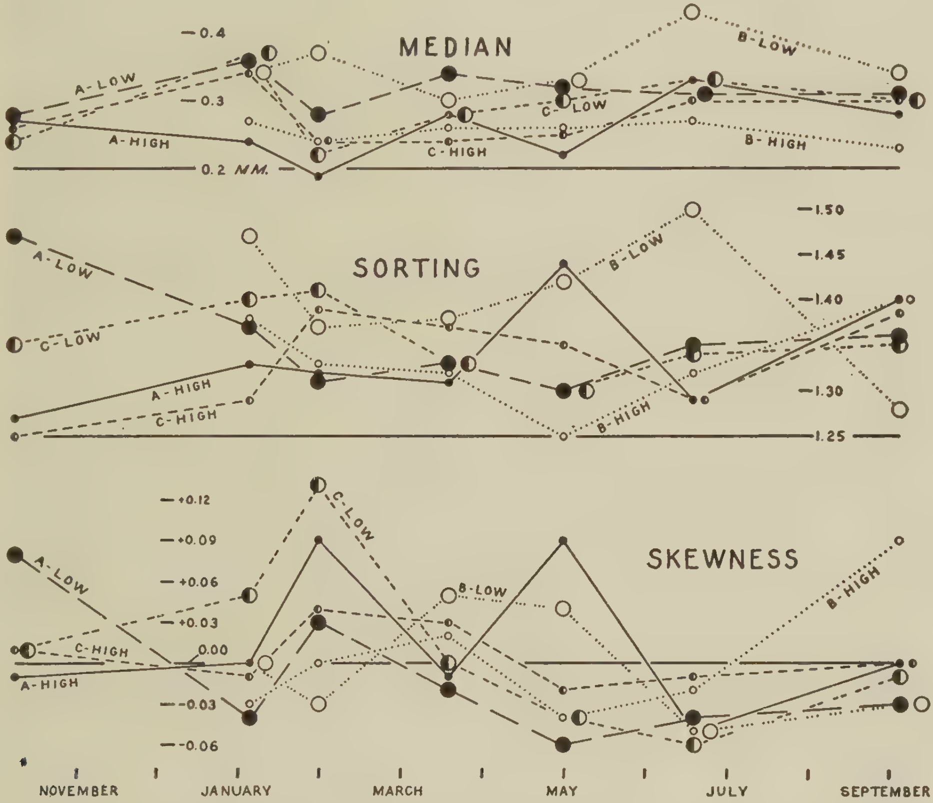

FIG. 3.—Median diameter, and coefficients of sorting and skewness at repeated stations plotted against time.

Skewness.—With clearly obvious exceptions, chiefly Stations A, high and C, low in February, possibly Station B, low in March and May, and A, high also in May, the graphed values of the skewness hang together very well. It should be noted that the exceptions cited for February are relatively large, positive values. Since the sampling followed closely the cutting of the dunes, as referred to above, the mode should be definitely on the small side of the median, and therefore these variations may not be exceptions. The swing between the June and September samplings is very uniform. Considering the whole graph it appears that the skewness values follow each other better than do the sorting values.

As demonstrated by the results of the February sampling, the cycle on this beach, with a plentiful supply of dune sand available to the waves in major storms, is very different from that on certain other beaches. For example, when Raymond and Stetson[1] attempted to sample Duxbury Beach on Massachusetts Bay at regular intervals, the first big storm in the fall removed all the sand from the beach leaving mainly cobbles and coarse gravel. By the following summer, the beach had become sandy again. Marshall (6) found that after a heavy storm, the sand on a New Zealand beach was considerably coarser. The 0.149 to 0.074 mm. grade size decreased from 25.9 per cent to 5.0 per cent. The 0.177 to 0.149 mm. grade decreased from 31.9 to 15.6 per cent. The next two larger size grades, to 0.297 mm. showed increases. He states that during calmer weather sand larger than 0.149 mm. gradually returns to the beach. Severe storms do not give this beach access to "new" material as is the case at Ipswich. Likewise conditions at Ipswich are very different from those on the outer beach of Cape Cod where the waves receive, within the cliff-backed section, large amounts of material ranging in size from clay through sand and gravel. Samples taken a year apart showed a general uniformity of trend in spite of cliff retreat amounting in places to 30 feet the winter preceding the first sampling and essentially no cutting during the intervening winter (7).

CONCLUSIONS

Sampling of three stations on the same beach, each with high and low tide samples, was repeated 6 times at one station and 7 times at the other two. The entire experiment covered slightly under eleven months. New material was available to the waves in the form of dunes which were cut only during periods of excessively high water. A plot of the medians, varying between the extremes of 0.19 and 0.43 mm. demonstrates that as the median at one location increases or decreases, the others tend to parallel its change. Stations which have the high tide median considerably smaller than the low preserve this relationship at subsequent dates despite absolute changes in value. Conversely stations with small difference between high and low show a small order of difference through the period of sampling. Thus plots of the median against time are approximately parallel, even though absolute values are greater or smaller.

On a beach of this general type a single high and low tide sampling at each station should show approximately the same range of difference between successive medians along the beach, and the same trend as would the average of a large number of repeated samplings.

To a lesser degree the coefficients of skewness and sorting also tend to change in unison with time. The fact that the medians change much more regularly adds support to the view that the median is the one most important characteristic of a clastic sediment. It is obviously better to base conclusions on the least variable characteristic.

The repetition of sampling illustrates the tendency to return to "normal" or to the equilibrium for the beach. Exceptional conditions, such as the storm which spread finer dune sand over the beach, reduce the median. Yet by the time the next samples were taken, the beach had returned approximately to the median values which preceded the storm. The medians for the June sampling are somewhat larger than the average. However, by the time of the September sampling, the values are back in the normal range. Thus we see, in addition to the important parallelism of change, the cyclical aspect of the return after each major disruption, to the character determined by each particular environment.

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[1] Personal communication.

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RECENT RESULTS IN SUBMARINE GEOPHYSICS

BY MAURICE EWING, G. P. WOOLLARD, A. C. VINE, AND J. L. WORZEL

CONTENTS

Page
Abstract.... 910
Introduction.... 910
Acknowledgments.... 911
Seismic refraction measurements in shallow water.... 911
    General statement.... 911
    Bubble pulses from under-water explosions.... 913
        Historical background.... 913
        Evidence obtained in 1941.... 913
        Evidence from refraction seismograms.... 914
        Practical importance.... 914
    Dispersion in the water wave.... 915
        General statement.... 915
        Analysis of the data.... 917
        Analysis by C. L. Pekeris.... 918
    Travel-time data and its interpretation.... 918
        General statement.... 918
        Solomons.... 918
        Jacksonville.... 918
        Virgin Islands.... 919
        Barbados.... 920
        Orinoco.... 921
Seismic refraction measurements in deep water.... 921
    Cable equipment used in 1937–1938.... 921
    Flotation equipment used in 1939–1940.... 921
    1940 operations.... 924
Eleuthera Island bathymetry.... 924
New method of sampling the ocean bottom.... 925
Photography of the ocean bottom.... 926
    General statement.... 926
    Geological information from under-water photographs.... 927
Long-range sound transmission in the ocean.... 928
    General statement.... 928
    Refraction effects.... 928
    Signal structure.... 928
    Practical applications.... 930
Conclusions.... 932
References cited.... 933

ILLUSTRATIONS

Figure Page
1. General arrangement for shallow-water seismic measurements.... 912
2. Variation of size of spherical explosion bubble with time from instant of explosion.... 914

3. First bubble pulse interval........ 915
4. Critical depth for bubble pulses for TNT charges........ 916
5. Typical dispersion curve........ 917
6. Travel-time curve for Orinoco deep station........ 919
7. Depth to basement from seismic measurements........ 920
8. Cable method of making deep seismic measurements........ 922
9. Float method of making deep seismic measurements........ 923
10. Bottom sampler........ 926
11. Schematic diagram of under-water camera........ 927
12. Typical temperature-depth curves in the North Atlantic Ocean........ 929
13. Typical velocity-depth curves in the North Atlantic Ocean........ 929
14. Sequence of arrival of sound-channel rays at approximately 1000 miles........ 930
15. Shadow zone at Eleuthera for Bermuda Island........ 931

Plate Facing page
1. Chart showing areas investigated........ 909
2. Typical shallow water seismograms........ 912
3. Oscillating gas bubble from detonator exploded under water........ 913
4. Oscillating gas bubble from detonator exploded under water........ 914
5. Seismogram showing dispersion in water wave........ 915
6. Bathymetric chart of Eleuthera Island........ 924
7. Seismograms from deep seismic measurements........ 926
8. Photographs of types of ocean bottoms........ 927
9. Photographs showing compaction, composite bottoms, and sand ripples........ 928
10. Photographs of plant and animal life on the sea floor........ 929
11. Ray paths in deep-sea sound channel........ 930
12. Seismogram of sound-channel transmission at 300 miles........ 932

ABSTRACT

During the war period nearly all the established methods of studying submarine geology were found to have military application, and, as a result of the impetus given to such work by government research and development contracts, new techniques were developed. Thus the field work of the war period has added considerably to knowledge gained through established methods and has demonstrated the potential usefulness to submarine geology of entirely new instrumentation.

The co-operation of geophysicists, submarine geologists, and oceanographers with the Navy's research program has been particularly close and effective. It has led to improvements in the methods of both deep-sea and shallow-water seismic surveys, to advances in the techniques of underwater photography, and to the developments of other rapid systems for collecting information about the sediments. Some examples of the results achieved by investigators at the Woods Hole Oceanographic Institution are presented.

As an example of an entirely new tool for the exploration of ocean basins, a method of acoustically scanning the floor of the deep ocean is explained. This method is particularly promising for the location of active submarine volcanoes and isolated submerged sea mounts which cannot be easily found by conventional sounding techniques.

INTRODUCTION

The present report covers investigations of submarine geology made by the authors during the years 1938–1945. The deep submarine seismic investigations started in 1937 were interrupted by war work at a point when they seemed about to produce results. Prior to the war, under-water photography had progressed successfully, and over 150 photographs had been taken. Some military applications of under-water photography were developed during the war. Included here with the earlier results are some geological results and instruments which resulted as by-products of the war activities. Most of the war work was done in connection with war contracts between the Woods Hole Oceanographic Institution, the Navy, and Section 6.1 of the National Defense Research Committee.

ACKNOWLEDGMENTS

Seismic refraction measurements in shallow water were supported by the Bureau of Ordnance and the Bureau of Ships, Navy Department, through contracts with the Woods Hole Oceanographic Institution. B. L. Snavely, J. E. Owen, Gale White, J. L. Worzel, and Maurice Ewing are primarily responsible for the geophysical work, which was done on board vessels of the U. S. Navy. G. P. Woollard produced the geological sections, and A. P. Crary contributed greatly to the bubble-pulse investigation in 1941.

Seismic refraction measurements in deep water were supported by The Geological Society of America and the Woods Hole Oceanographic Institution. Most of the work was done on board the ketch ATLANTIS of the Woods Hole Oceanographic Institution, although some development work was done on the ketch CULVER of the Royal Society. Part of the work was aided by the facilities of the Bermuda Biological Station and Lehigh University. A. C. Vine, J. L. Worzel, G. P. Woollard, and Maurice Ewing are primarily responsible for the technical work.

Eleuthera Island bathymetry was done on board the U.S.C.G.R. VALOR under the supervision of Marshall Schalk.

Work on a new method of sampling the ocean bottom was supported by Section 6.1 of the National Defense Research Committee through a contract with the Woods Hole Oceanographic Institution. J. L. Worzel, A. C. Vine, and Maurice Ewing are primarily responsible for the technical work.

Photography of the ocean bottom was supported originally by the National Geographic Society and the Woods Hole Oceanographic Institution. War-time modifications were supported by Section 6.1 of the National Defense Research Committee through contracts with the Woods Hole Oceanographic Institution. A. C. Vine, J. L. Worzel, and Maurice Ewing are responsible for the technical work.

Work on long-range sound transmission in the ocean was supported by Section 6.1 of the National Defense Research Committee and later by the Bureau of Ships, Navy Department, through contracts with the Woods Hole Oceanographic Institution. J. L. Worzel, R. J. McCurdy, J. A. Peoples, Jr., N. C. Steenland, E. L. Newhouse III, D. T. Parsons, W. S. von Arx, and Maurice Ewing are primarily responsible for the technical work.

SEISMIC REFRACTION MEASUREMENTS IN SHALLOW WATER

GENERAL STATEMENT

Incidental to work done jointly by the Woods Hole Oceanographic Institution and the Navy Department, seismic refraction data were obtained in coastal waters in

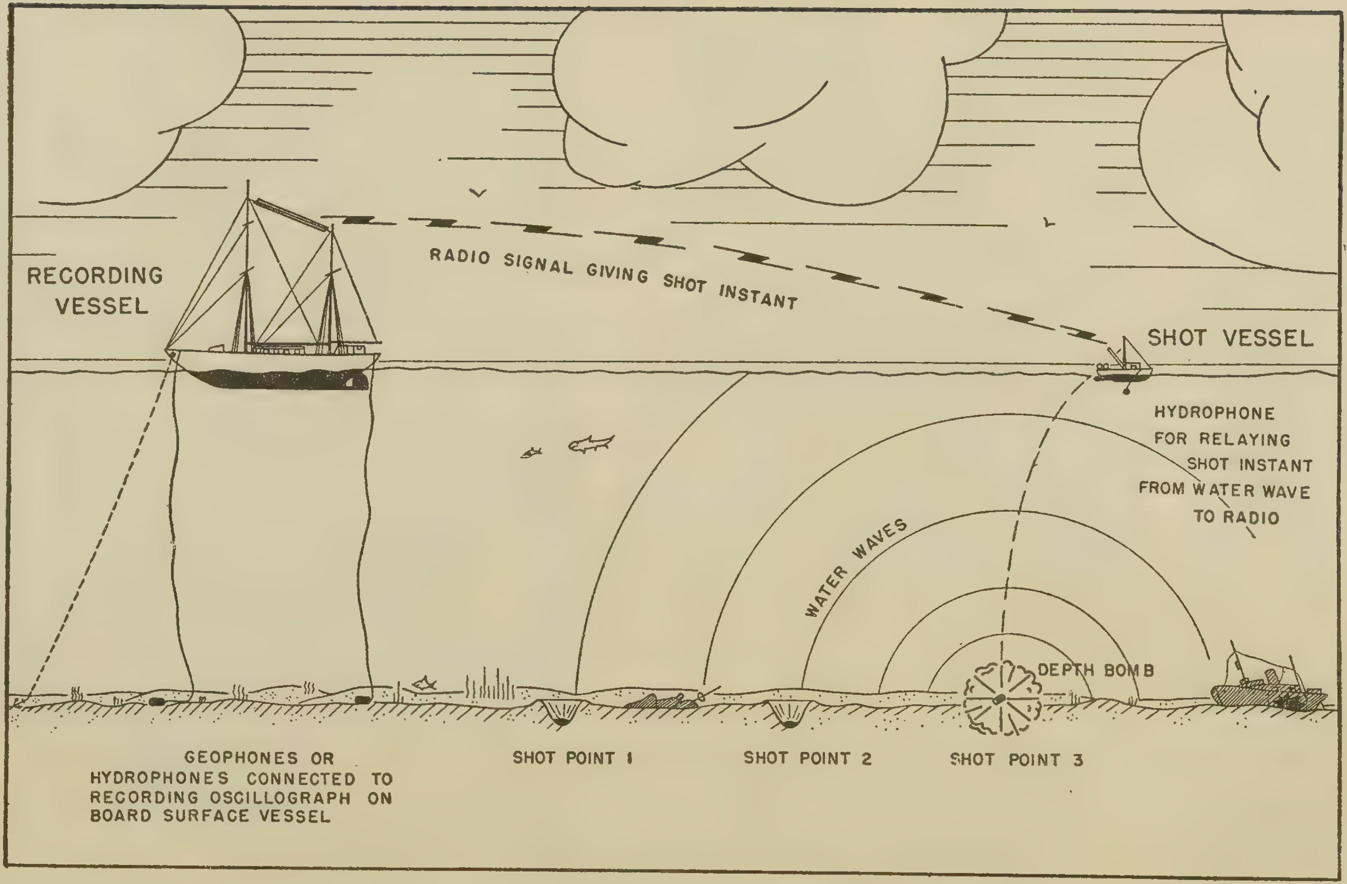

RECORDING VESSEL
RADIO SIGNAL GIVING SHOT INSTANT
SHOT VESSEL
HYDROPHONE FOR RELAYING SHOT INSTANT FROM WATER WAVE TO RADIO
WATER WAVES
DEPTH BOMB
GEOPHONES OR HYDROPHONES CONNECTED TO RECORDING OSCILLOGRAPH ON BOARD SURFACE VESSEL
SHOT POINT 1
SHOT POINT 2
SHOT POINT 3

FIGURE 1.—*General arrangement for shallow-water seismic measurements* depth less than 600.

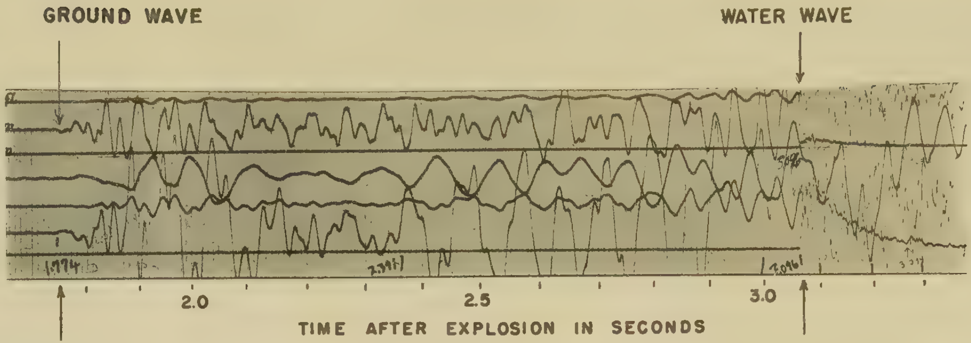


Figure 1. Typical Seismogram

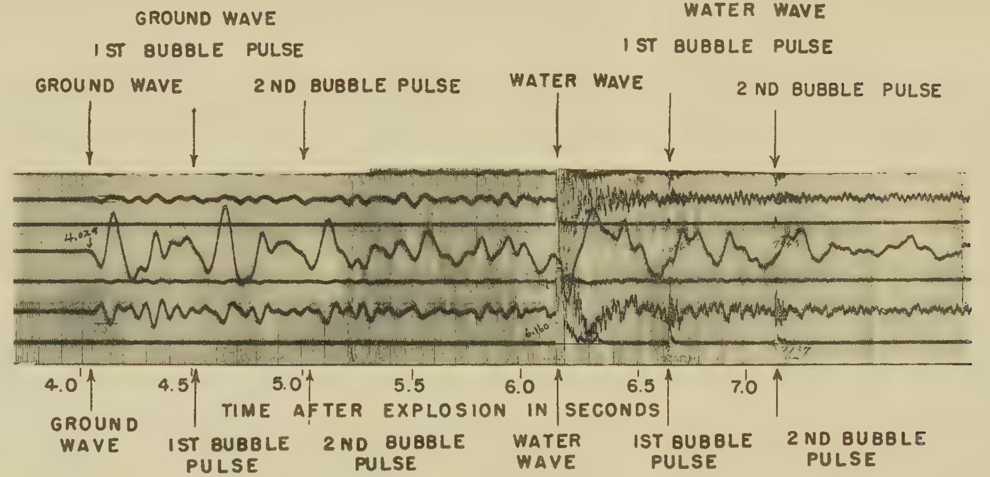


Figure 2. Seismogram Showing Effect of Bubble Pulses

TYPICAL SHALLOW-WATER SEISMOGRAMS

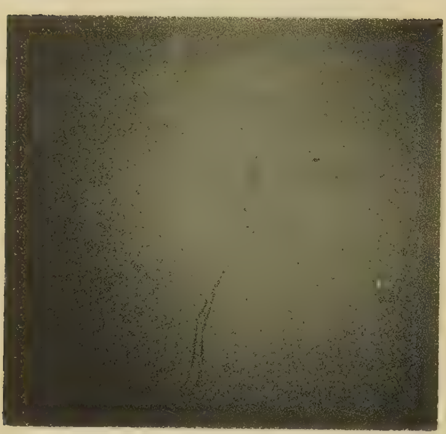


Figure 1. .0000 Sec.

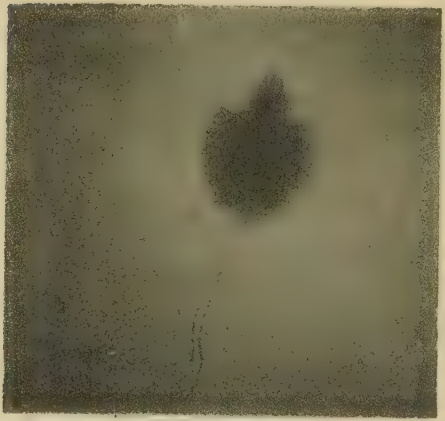


Figure 2. .0014 Sec.

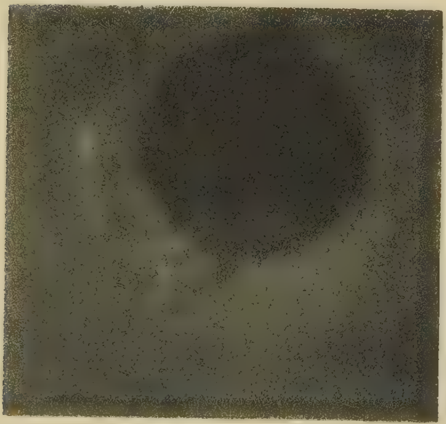


Figure 3. .0028 Sec.

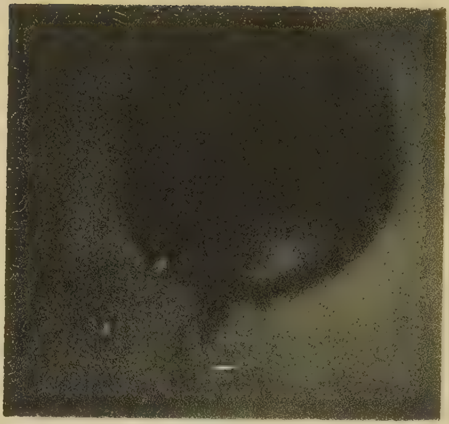


Figure 4. .0043 Sec.

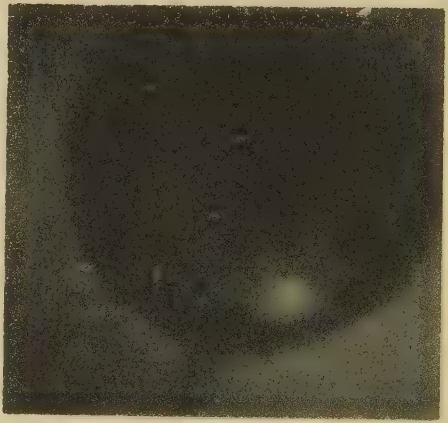


Figure 5. .0098 Sec.

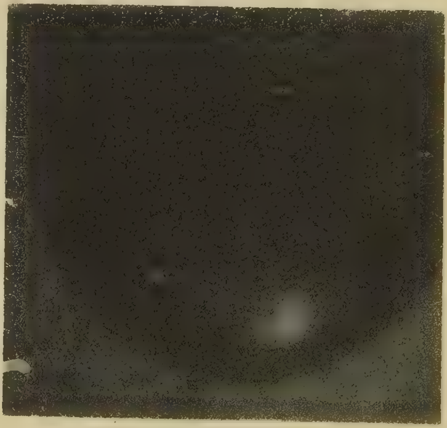


Figure 6. .0168 Sec.

OSCILLATING GAS BUBBLE FROM DETONATOR EXPLODED UNDER WATER depths of 10 and 20 fathoms. These data extend to new areas our earlier seismic work in the submerged Atlantic Coastal Plain (Ewing, Crary, and Rutherford, 1937). Measurements were made in Chesapeake Bay, off Jacksonville, Florida, off St. Thomas, Virgin Islands, off Barbados, and on the Orinoco Delta. These stations are shown in Plate 1.

A total of 446 shots were fired, ranging from half a pound to 300 pounds of TNT. Of these, half were on bottom, and half were at mid-depth. Distances between shot and recording positions ranged from a few hundred feet up to 27 miles and were determined by measuring the travel time of the water wave. The shot instant was transmitted to the recording vessel by radio. All recording was done with an oscillograph on board the USS SALUDA, using two hydrophones and one geophone, all placed close together on bottom. The hydrophones and the geophone gave similar records. The general arrangement is shown in Figure 1.

Figure 1 of Plate 2 is a typical record which shows a series of low-frequency ground waves followed by a water wave of characteristically higher frequency. The time marks are at intervals of 1/100 second. The multiple traces correspond to different frequency bands—in some cases from different acoustical pickups and in others from different filters applied to the output of a single pickup.

BUBBLE PULSES FROM UNDER-WATER EXPLOSIONS

Historical background.—A phenomenon first reported by Blochmann (1898) but not widely known by geophysicists is of importance in all under-water work with explosives. He noted that a single under-water explosion produced two or more definite pressure waves as though there were several separate explosions each less intense than the preceding. His explanation was that the gas bubble formed by the products of the explosion expands to a size so large that the pressure of the gas is below that of the surrounding water. The bubble then contracts sufficiently to produce a very high pressure and emit a new sound wave.

Evidence obtained in 1941.—While working on another problem in 1941, we encountered multiple sounds from single explosions. Unaware of Blochmann's work, we arranged for H. E. Edgerton to take high-speed motion pictures of detonators fired under about 3 feet of water. These pictures (*see* Pls. 3 and 4) show that the gas bubble definitely oscillates. The radius of the oscillating gas bubble as a function of time, determined from these photographs, is shown in Figure 2. Oscillograms made at the time these pictures were taken showed that a sound pulse was emitted each time the bubble reached minimum radius.

The next stage of the investigation was a very rough determination of time interval for the first bubble oscillation as a function of depth and charge size. This led to the empirical equation:

$$T = 12.5\, W^{1/3} (h + 33)^{-1} \tag{1}$$

when W is the weight of TNT in pounds, h is the depth of the charge in feet, and T is the time interval in seconds. Usually three or four impulses were recorded from each explosion, with decreasing time intervals and intensities for successive pulses.

More recent work by several investigators, and extension of the data to greater depths, have shown this equation to be in error. The corrected equation is:

$$T = 4.19\, W^{1/3}\, (h + 33)^{-5/6} \qquad (2)$$

Evidence from refraction seismograms.—Most of our refraction seismograms show evidence of this phenomenon. For example, the seismogram shown in Figure 2 of Plate 2 has three successive water-wave signals. On this record there are also three ground-wave signals which have the same time intervals between themselves as the water waves. This proves that there were in effect three explosions at intervals of roughly half a second, each of which gave a complete set of ground and water waves. Figure 3 is a plot of the first bubble-pulse intervals for all shots. The curves in this figure are drawn from equation (2) and are in good agreement with the observations.

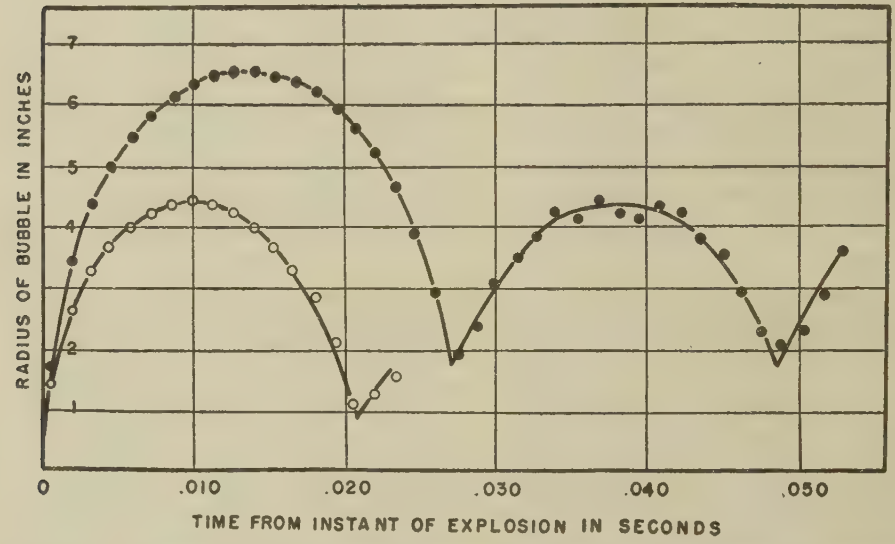


FIGURE 2.—*Variation of size of spherical explosion bubble with time, from instant of explosion* O—Lead azide detonator. ●—#6 tetro detonator. Taken from high speed motion pictures—744 pictures/sec. Sound impulse starts at each minimum.

Practical importance.—At least one bubble-pulse sound emission was observed on 63 per cent of all our bottom shots and on 87 per cent of the mid-depth shots. The great majority of the mid-depth shots showed two or three bubble pulses. Obviously the successive sound emissions from the oscillating gas bubble can produce serious interference in seismic prospecting of water-covered areas, particularly in reflection work.

The multiple sound emissions from explosions in water-filled quarries, for which no explanation could be found when they were observed some 10 years ago, are now explained. (*See* records 69–70–6 and 69–71–4, Leet and Ewing, 1932, p. 165.)

As pointed out recently by Lay (1945), the multiple sound emission may be eliminated by placing the charge near enough to the water surface so that it blows out on

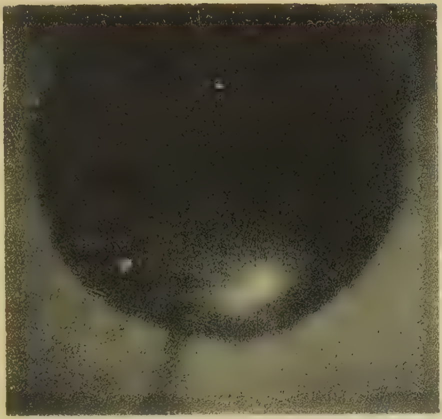


FIGURE 1. .0238 SEC.

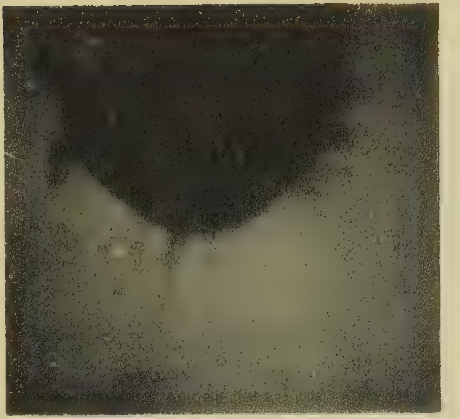


FIGURE 4. .0420 SEC.

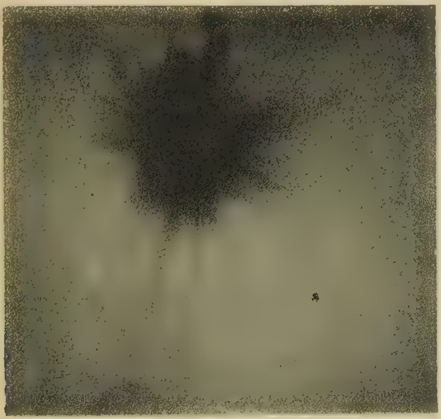


FIGURE 2. .0308 SEC.

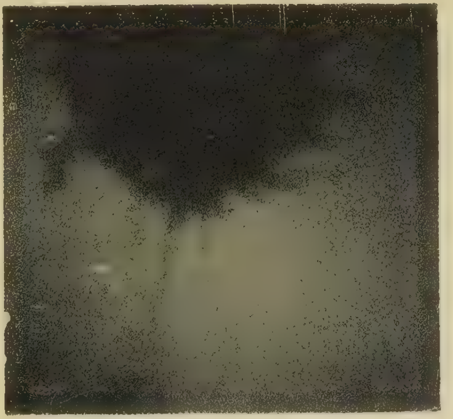


FIGURE 5. .0476 SEC.

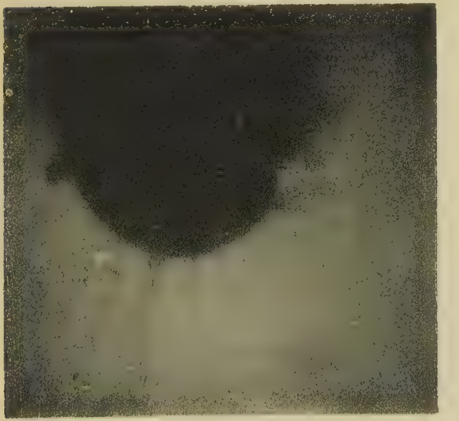


FIGURE 3. .0364 SEC.

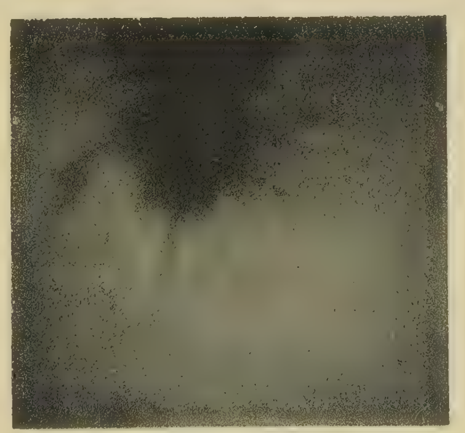
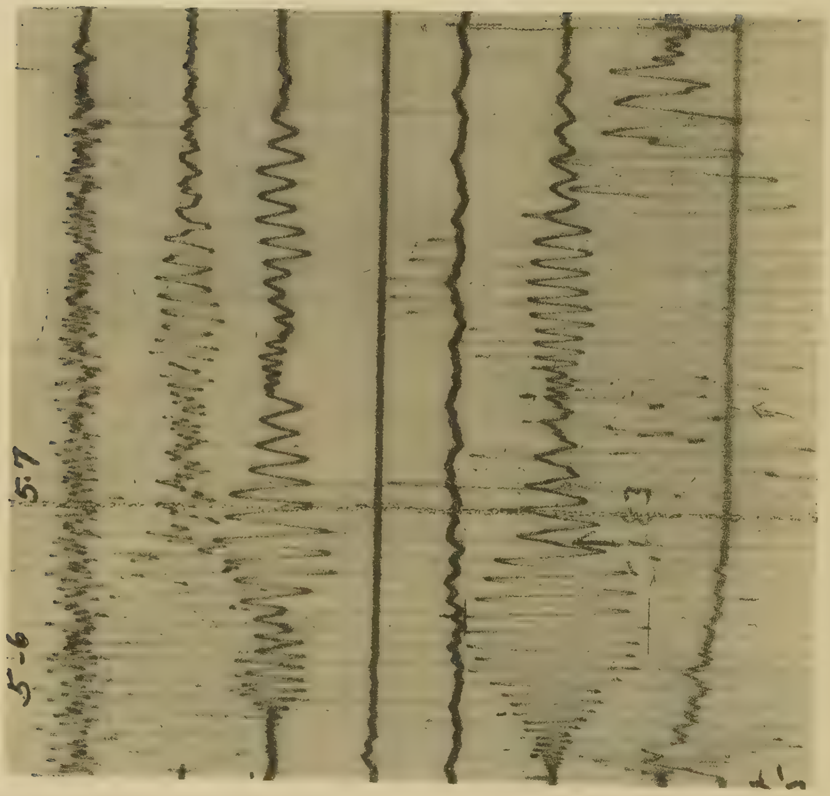


FIGURE 6. .0532 SEC.

OSCILLATING GAS BUBBLE FROM DETONATOR EXPLODED UNDER WATER



SEISMOGRAM SHOWING DISPERSION IN WATER WAVE

Dispersion in Water Wave in Shot No. 91 at Jacksonville Shoal

Depth of Water = 60 feet, Charge Weight = 5 lbs.; Charge and Hydrophone beached on bottom.

the first expansion of the bubble. A curve showing the critical depth for bubble pulses as a function of weight of TNT, which has been compiled from various sources, appears in Figure 4.

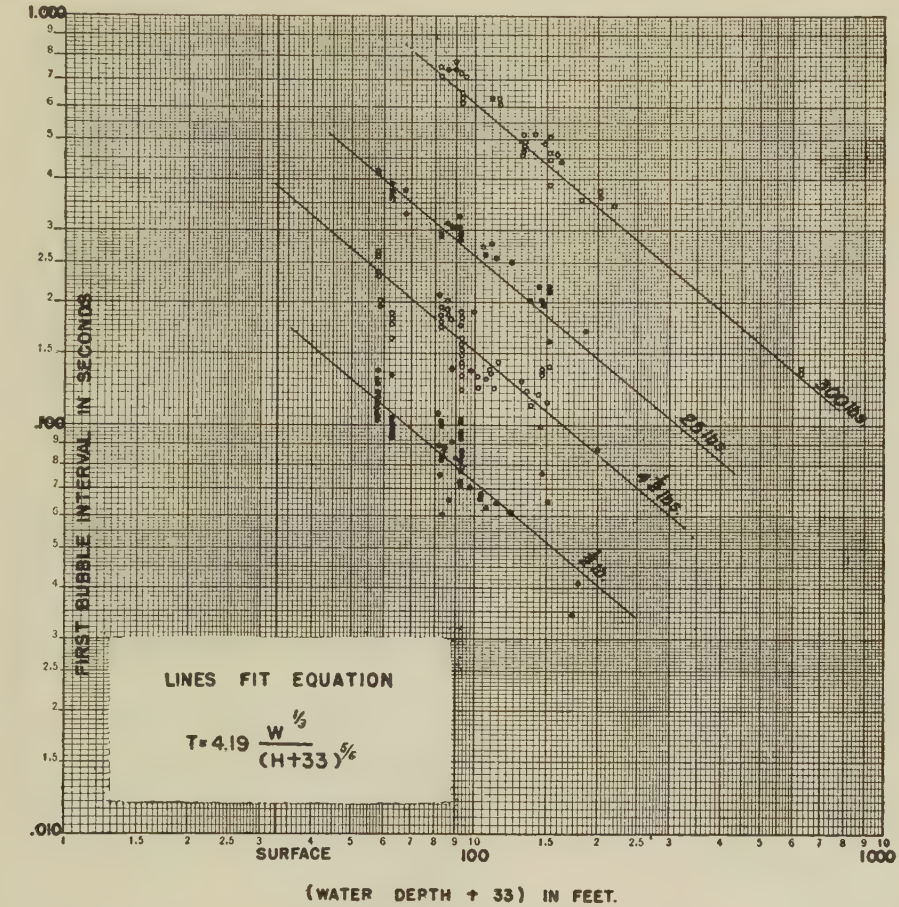


FIGURE 3.—*First bubble pulse interval*

DISPERSION IN THE WATER WAVE

General statement.—Dispersion in the water wave, with the higher-frequency sound arriving ahead of the lower, was observed at all stations. Although this phenomenon was observed by Ewing as early as 1927 in the course of seismic prospecting operations in the coastal lakes of Louisiana, the present work offered the first opportunity to obtain adequate data for its study.

Plate 5 shows the water-wave portion of a typical seismogram from the Jacksonville Shoal station. The water depth was 60 feet, and the charge was 5 pounds of TNT which was fired on bottom at a distance of about 5 miles. The approximate

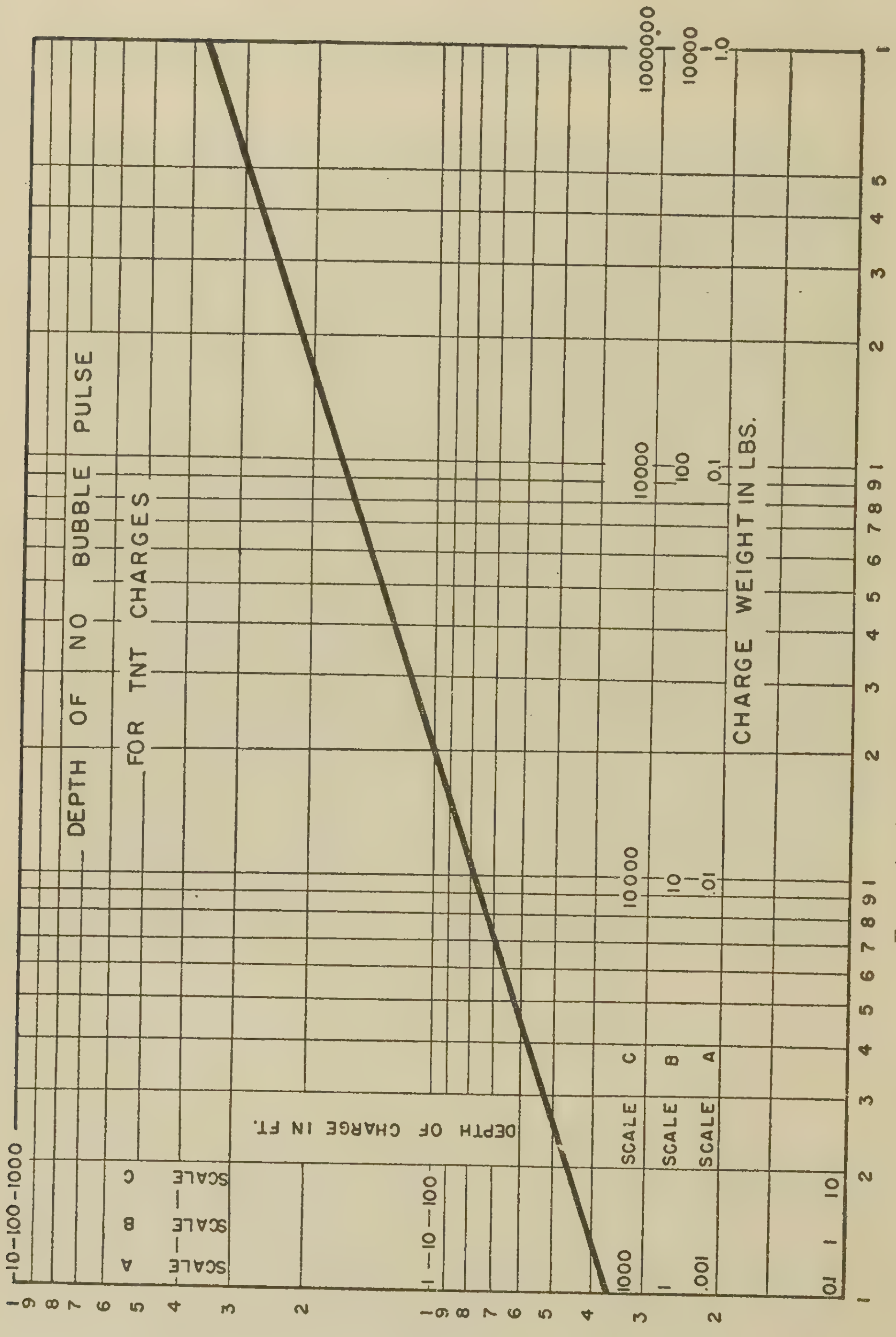


Figure 4.—*Critical depth for bubble pulses for TNT charges*

time in seconds, measured from the instant of the explosion, is marked across the top of the record. The water wave from the explosion is a train of waves starting at about 5.55 seconds, and that from the bubble pulse is a similar but weaker train starting at about 5.75 seconds. Traces 3 and 6 in Plate 5 show that the sound velocity varies by about 3 per cent for the frequency range from 500 to 60 cycles per second. It is generally recognized that no velocity variation of this magnitude occurs in water, and our own measurements in deep water have never shown dispersion. Hence, it is clear that the observed dispersion is related to the shallow water. This effect occurs only when the wave length of the sound approaches the water depth. Under these conditions ray acoustics do not hold, and wave acoustics must be used. By using the arrival time of the highest-frequency sound, the normal velocity of sound in sea water can be used for computing distance.

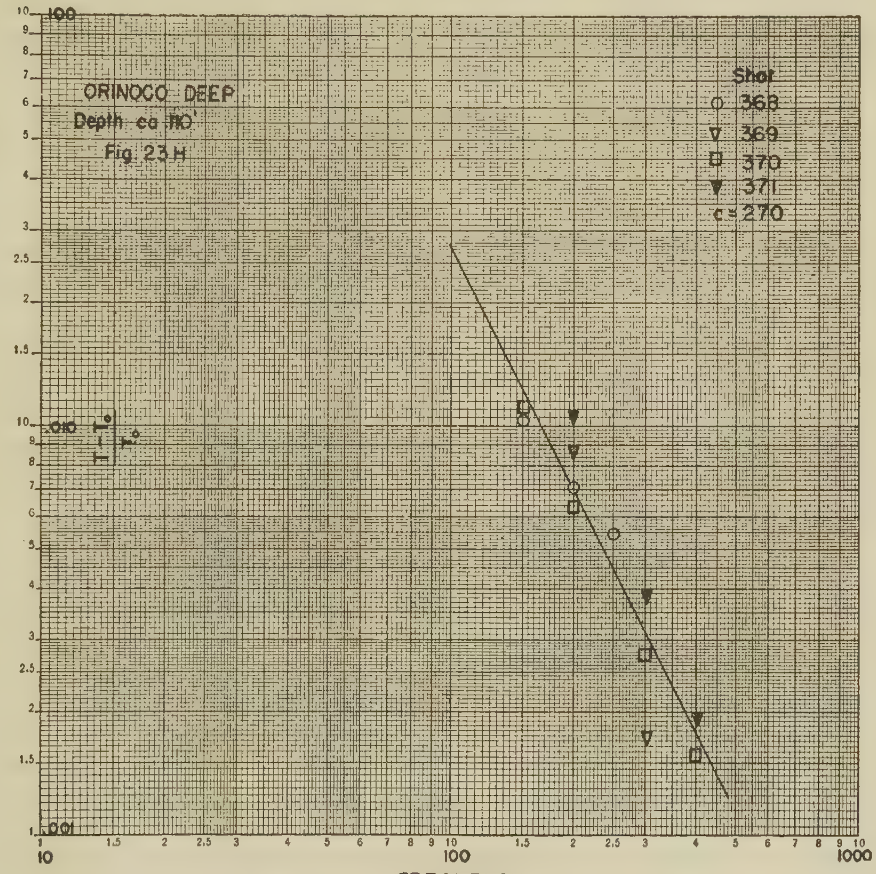


FIGURE 5.—*Typical dispersion curve*

Analysis of the data.—The method of analyzing this dispersion was to select about four seismograms at different distances at each station. In each of these, four places were selected where the travel time, T, and the frequency, F, of the water waves could be read. A plot of log $\frac{T - T_o}{T_o}$ against log F was made for each station where T_o is the travel time for the highest-frequency sound received. Figure 5 is a typical plot. It should be noted that the ordinate $(T - T_o)/T_o$ is identical with $(V_o - V)/V$ which is defined as the dispersion. All of the curves plotted as described above had slopes of the order of -2, indicating the dispersion formula

$$V = V_0 (1 - \frac{C}{F^2}) \tag{3}$$

where C was a constant for each station.

Analysis by C. L. Pekeris.—These results and the original data were turned over to C. L. Pekeris, who had done theoretical work on a similar problem. He established a complete and detailed explanation of the observed dispersion in terms of bottom structure.[1]

Measurement of the dispersion in the water wave may be interpreted by this theory to determine the sound velocity in the ocean bottom to a depth approximately equal to the depth of the water. Although it has been used to date only in shallow water, the method is feasible for oceanic depths. Preliminary plans for observations in the deep ocean, with suitable instruments to observe these interfacial waves, have been made.

TRAVEL-TIME DATA AND ITS INTERPRETATION

General statement.—Travel-time graphs for each station were plotted, and depths were calculated by the standard refraction-seismic methods (*see* Ewing, Crary, Rutherford, 1937). One of these plots is shown in Figure 6. The distance between the shot and the receiver was obtained in every case from the travel time of the water wave. Although it was not possible to shoot reversed profiles for obtaining the slopes of the strata, this omission should not lead to serious error in the depth determination, since the profiles were made parallel to the shore line and along the probable strike. Figure 7 shows the depth to basement calculated at each station.

Solomons.—At Solomons, off the mouth of the Patuxent River in Chesapeake Bay, the depth to basement at the shoal seismic station was 3050 feet. At the deep seismic station about 4 miles to the east, the depth to basement was 2950 feet. The probable depths based on geologic evidence were 2800 feet and 3100 feet respectively. These were determined on the assumption of a constant slope from the Fall Line near Quantico, Virginia, 40 miles to the westward, to the Ohio Oil Company's L. G. Hammon, No. 1 well near Salisbury, Maryland (Richards, 1945), 50 miles to the east.

Jacksonville.—The seismic determinations of the depths to basement were 6250 feet at the shoal station and 7600 feet at the deep station. As there were no well data in the immediate vicinity, the basement slope indicated by these determinations was used to project the basement surface from the nearest well, St. Mary's River Oil Corporation, Hilliard Turpentine Company No. 1, about 45 miles to the northwest, near Hilliard, Florida, to these stations. The projected depths were 5900 feet for the shoal station and 7200 feet for the deep station.

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[1] Submitted for publication to The Geological Society of America

Virgin Islands.—The Virgin Island Shoal station starts a few hundred yards south of Water Island and runs about E. 10° S. for a distance of about 10 miles to a depth of about 1300 feet. The velocity is about 13,160 ft./sec. The underlying rock has a velocity of 19,560 ft./sec., and the interface between the two is plane over the 10-mile extent of the station. Auxiliary shots on a southerly course show that the plane extends to a point about 4 miles south of Water Island, where it terminates in a steep downslope. This termination occurs about 3 miles inside the 100-fathom curve. The data at this station are excellent.

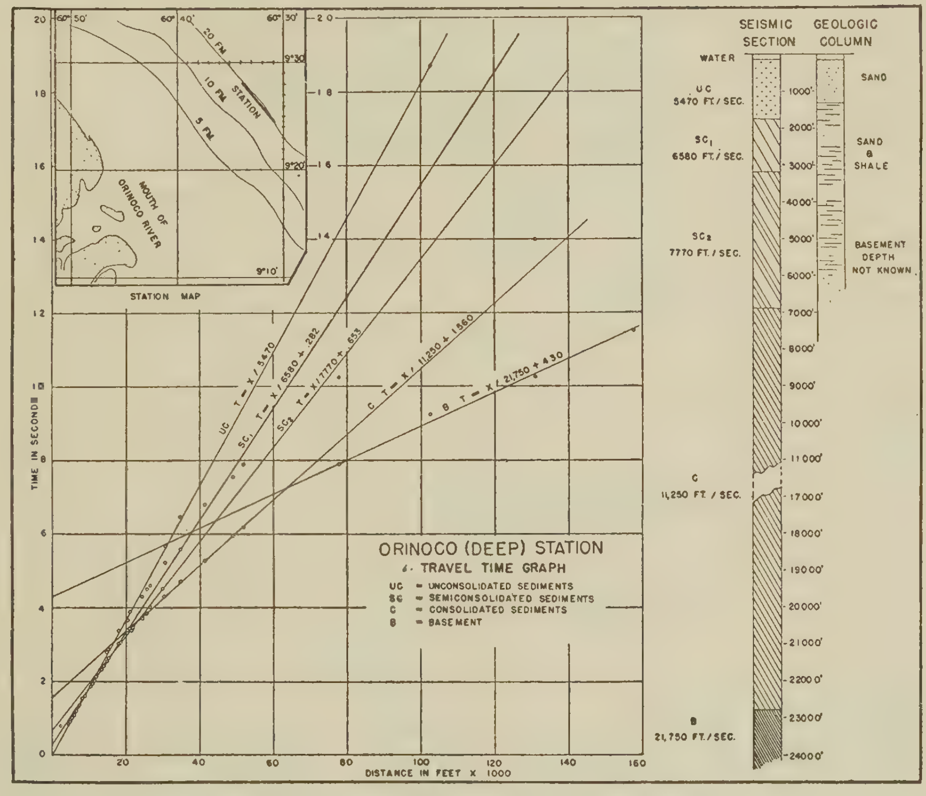


FIGURE 6.—*Travel-time curve for Orinoco deep station*

(a) Station map. (b) Travel-time graph. (c) Seismic and geologic columns

The Virgin Islands Deep station starts near Outer Brass Island and runs N. 30° W. about 8 miles. The surface rock has a velocity of 12,880 ft./sec. and extends to a depth of 650 feet. An intermediate layer has a velocity of 15,940 ft./sec. and extends to a depth of 2800 feet below sea level. The rock beneath this has a velocity of 18,980 ft./sec. but extends only a little more than 5 miles from Outer Brass Island, or about 6 miles inside the 100-fathom curve, and terminates in a steep downslope.

Auxiliary shots on a westerly course to distances up to 9 miles show that the layer depths remain unchanged along this course. An alternative explanation of the data at this station is that instead of an intermediate layer there is a slope in the surface of the basement layer for about 3 miles in the vicinity of Outer Brass Island. This interpretation would increase the depth to basement but would leave other features of the picture unchanged.

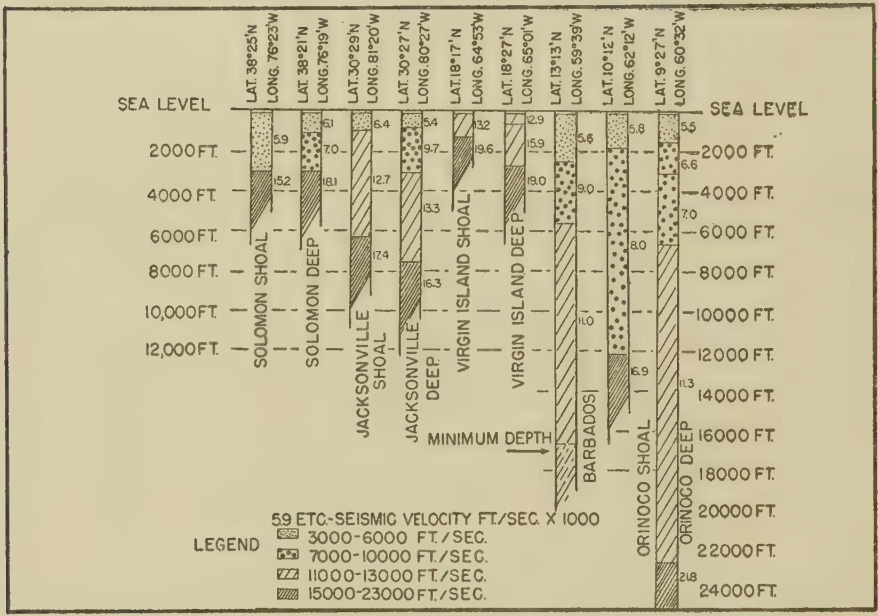


FIGURE 7.—*Depth to basement from seismic measurements*

The basement (19,000 ± ft./sec.) found at 1300 feet south of Saint Thomas and at 2700 feet north of it shows a very flat surface which suggests peneplanation. Both of these levels are below the lowest peneplane (near sea level at Saint Thomas) reported by Meyerhoff (1926). This basement is considered to be the igneous complex which forms the basis on which the entire platform is built.

The top layer (velocity 13,000 ft./sec.) is considered to be composed of tertiary and later sediments; the upper part at least is coraline. The values found for the velocities of these two stations again answer in the affirmative the question which has been debated at every proposal of seismic investigations of atolls: Are the velocity relations such that the igneous platform may be detected beneath a coraline cover? The question was first answered in Bermuda, where velocities of 8800 ft./sec. and 16,000 ft./sec. were observed for the coraline cover and for the igneous platform whose depth was about 250 feet (Woollard and Ewing, 1939).

Barbados.—The station made along the western shore of Barbados is of especial interest because that island has a negative gravity anomaly of 134 milligals and lies exactly in the strip of negative gravity anomalies which parallels the West Indian island arc (Ewing, 1937). The usual interpretation of the negative gravity anomalies, and the fact that all the exposed rocks on Barbados are sediments from both deep and shallow deposition, led to the expectation of a large total thickness of sediments. The seismic profile revealed a velocity of 5620 ft./sec. to a depth of 2600 feet, 9030 ft./sec. to 6100 feet, and 11,040 ft./sec. to an undetermined depth which must exceed 16,600 feet.

Orinoco.—At Orinoco the shoal station was made in the southwest part of the Gulf of Paria, and the depth to basement was 12,200 feet. At the deep station, about 100 miles to the southeast, and in the Atlantic Ocean at the mouth of the Orinoco River the depth to basement was 22,700 feet. There were no available well data to check these seismic determinations.

SEISMIC REFRACTION MEASUREMENTS IN DEEP WATER

CABLE EQUIPMENT USED IN 1937–1938

The seismic measurements made in the Atlantic Ocean basin in 1937–1938 were described at the 1938 meeting of the Geological Society.

The gear as then used was strung along a steel cable. From the ship a steel cable led to a large pressure vessel containing a four-channel oscillograph, from which led a 3400-foot electric cable with four geophones spaced 400 feet apart and three bombs 1000 feet apart. (*See* Figure 8.) Lowerings were made with this equipment; but only one, 180 miles south of Newport, Rhode Island in 1635 fathoms, gave geologic information.

At this station, a bottom velocity of 5700 feet per second was obtained, but basement was not reached. An assumed basement velocity of 18,000 feet per second indicated a depth of sediments greater than 600 feet.

This equipment was unsatisfactory for several reasons:

(1) The oscillograph and geophones would often be affected by unavoidable mechanical disturbances coming down the cable.

(2) When unknown currents opposed the motion of the ship, the gear was often piled on top of itself, instead of being in a line with the proper spacing.

(3) When currents aided the motion of the ship, the gear and the insulation of the of the long electric cables was damaged by dragging on the bottom.

FLOATATION EQUIPMENT USED IN 1939–1940

The cable method was abandoned in favor of a float method, after preliminary calculations and tests. At first it was proposed to lower all of the gear on one float (Ewing and Vine, 1938), using an inclined plane to cause the gear to be laid in a straight line along bottom.

At this stage it was realized that the sounds reaching the geophone from the bomb after one and two surface reflections could be used to calculate the firing time of the bomb without the use of a connecting wire. This point was confirmed by a study of the 1937–1938 records. Plans were then made to lower each bomb and each recording unit on its own float and without any interconnection. (*See* Figure 9.)

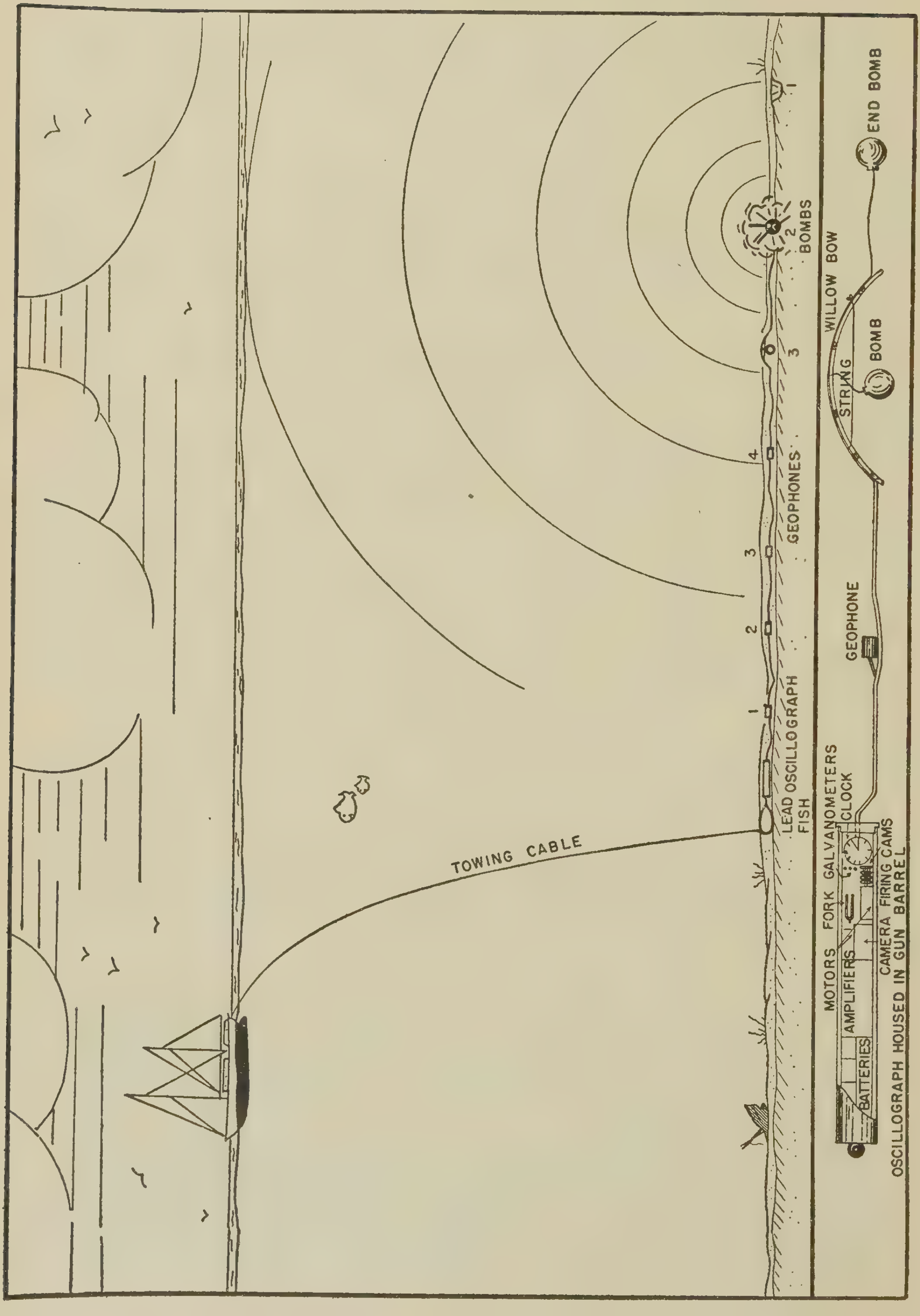

TOWING CABLE
LEAD FISH
OSCILLOGRAPH
1
2
3
4
GEOPHONES
3
2
BOMBS
1
WILLOW BOW
STRING
BOMB
END BOMB
GEOPHONE
MOTORS
FORK
GALVANOMETERS
CLOCK
AMPLIFIERS
BATTERIES
CAMERA
FIRING CAMS
OSCILLOGRAPH HOUSED IN GUN BARREL

FIGURE 8.—*Cable method of making deep seismic measurements*

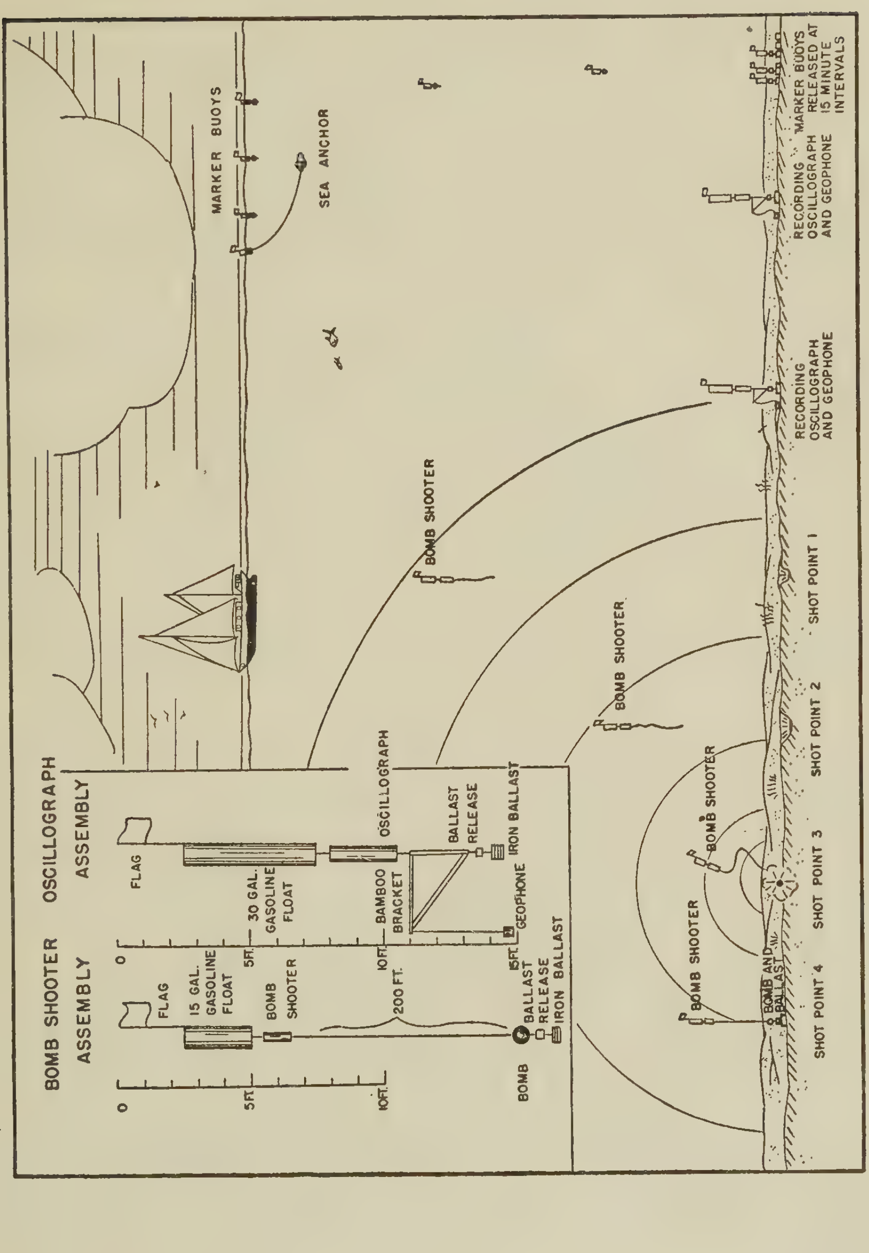

BOMB SHOOTER ASSEMBLY
OSCILLOGRAPH ASSEMBLY
0
5FT.
10FT.
FLAG
15 GAL. GASOLINE FLOAT
BOMB SHOOTER
200 FT.
BOMB
BALLAST RELEASE
IRON BALLAST
0
5FT.
10FT.
15FT.
FLAG
30 GAL. GASOLINE FLOAT
BAMBOO BRACKET
OSCILLOGRAPH
BALLAST RELEASE
IRON BALLAST
GEOPHONE
MARKER BUOYS
SEA ANCHOR
BOMB SHOOTER
BOMB SHOOTER
BOMB SHOOTER
BOMB SHOOTER
BOMB AND BALLAST
SHOT POINT 4
SHOT POINT 3
SHOT POINT 2
SHOT POINT 1
RECORDING OSCILLOGRAPH AND GEOPHONE
RECORDING OSCILLOGRAPH AND GEOPHONE
MARKER BUOYS RELEASED AT 15 MINUTE INTERVALS

FIGURE 9.—*Float method of making deep seismic measurements*

Each oscillograph was housed in an aluminum pressure case and was lifted by a 30-gallon rubber tank float filled with gasoline. Iron ballast was used to make the assembly sink to the ocean floor where the ballast and the geophone would both rest on the bottom. Synchronized clocks started the oscillograph and fired the bombs in sequence. After the records had been obtained, the ballast was dropped by a release mechanism, and the apparatus floated to the surface where it was recovered. The loss of instruments was reasonably low. Only one oscillograph and nine bomb shooters were lost out of 74 units lowered. Five of these losses were from known causes which have been eliminated. Many pieces of test equipment were also lowered and retrieved.

During the spring of 1939 preliminary tests were made at Bermuda, and the system was further developed in 1940. It eliminated the cable problems and proved to be far superior to the cable method for the following reasons:

(1) The spacing between bombs and oscillographs could be easily extended to provide a station spread sufficient to reach very deep basement.

(2) The work could be done from any seaworthy vessel. Previously, the need for a long cable and special winch had restricted the work to special vessels.

(3) The greatest depths in the ocean could be worked nearly as well as lesser depths.

(4) No one piece of cable was over 200 feet long; this greatly facilitated the handling of the gear.

1940 OPERATIONS

In 1940, operating from Woods Hole in the ATLANTIS, a station was occupied 140 miles south of Cape Cod, Massachusetts, in 1400 fathoms of water.

The record obtained (Pl. 7) shows the ground wave, direct water wave, and the first and second echoes from the surface. This station had a spread of 4200 feet, and a bottom velocity of 5400 ft./sec. was obtained. No indication of high-speed basement rock was on the record. Assuming 18,000 ft./sec. for basement velocity, the depth of sediments was calculated to be greater than 1500 feet.

Later in the summer, a station was occupied 300 miles northwest of Bermuda in 2600 fathoms with a spread of 3300 feet. A velocity in the bottom of 5300 ft./sec. was obtained, and the thickness of sediments was calculated to be greater than 1200 feet.

It is unfortunate that, due to minor instrumental difficulties, only one bomb was recorded by one oscillograph at each station. However, these difficulties were not fundamental, and the quality of the records obtained proved the feasibility of the method. At this point the war stopped the investigations before other stations could be occupied.

We consider that a satisfactory method of shooting refraction profiles on the floor of the ocean has been developed.

ELEUTHERA ISLAND BATHYMETRY

A reconnaissance survey of the offshore slope of Eleuthera Island, Bahamas (Pl. 6) has been made by the U.S.C.G.R. VALOR. The soundings were made with a fathometer and have not been corrected to vertical soundings. Positions of the soundings relative to the beach were fixed with radar.

Conservative contours were drawn to fit the soundings. The solid-line portions have good control, while the dashed portions are less certain. Beneath the contoured chart is a section parallel to the shore line showing a variation of depth as large as 12,000 feet. This traverse follows a line of continuous soundings.

The topography is complicated by the numerous canyons which furrow the steep slope to depths greater than 12,000 feet. These canyons have much steeper slopes than those of either coast of the United States (Pl. 6). The general seaward slope is about 1300 feet per mile, which is the same order of magnitude as that given by Hess (1933) for the walls of the Tongue of the Ocean. However, the break in slope which he found at about 4000-foot depth was not observed on the eastern slope of Eleuthera. In Plate 6, the general seaward slope of Eleuthera along section EE is comparable with that of the top of the Dakota sandstone across the northern rim of the San Juan Basin, one of the steepest structural profiles on the tectonic map of the United States.

NEW METHOD OF SAMPLING THE OCEAN BOTTOM

During the past 3 years, several thousand bottom samples have been obtained on the continental shelf with a newly developed bottom sampler. The new sampler can be used underway at speeds of 8 knots or more, thus enabling large areas to be covered. The operation of the instrument is so simple that the time for lowering ranges from about 8 minutes in 100 fathoms of water to about 3 minutes in 10 fathoms. These features permit more detailed sampling than is possible with previous samplers (Hough, 1939) which required the vessel to be stopped. Because the ship's speed and course are not altered, the relative positions of stations are also greatly improved.

The instrument (Fig. 10) is simple and inexpensive; it consists of a brass or iron weight with fins on the tail and a sampling tube on the nose. The hoisting cable is attached just forward of the center of gravity.

While descending, the cable is allowed to pay out faster than the ship moves ahead, thus permitting the sampler to fall. The tail fins cause the sampler to strike bottom nose first. Bottom contact is indicated by the cable going slack. The brake is applied, the cable becomes taut, the sampler rises and is reeled in. This type of operation has proven very reliable; for in some 1200 bottom samples taken by our group, instrument losses have been negligible.

The size of the sample obtained in a lowering is about half a pint, although a bigger sampler could be made to obtain larger samples and to operate at greater depths. The depth of penetration was several inches, and the sampler functioned satisfactorily in mud, sand, gravel, and has even brought up considerable coral. Other models which had trap doors to confine the sample and eliminate washing have been built and successfully operated. However, as samples taken with the original instrument showed little tendency to wash, the trap-door models were seldom used.

The ability to take samples underway is a particular advantage if the vessel is equipped with a continuously recording fathometer, because the position from which the sample is taken can be accurately located with relation to the bottom topography. An attachment has been built into some samplers to record the depth at which each sample is taken.

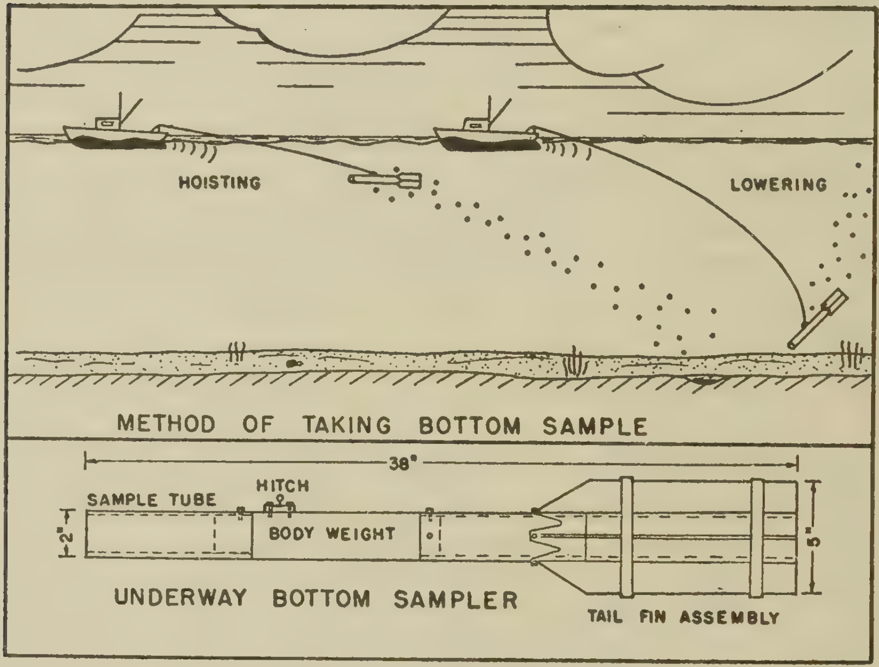


FIGURE 10.—*Bottom sampler*

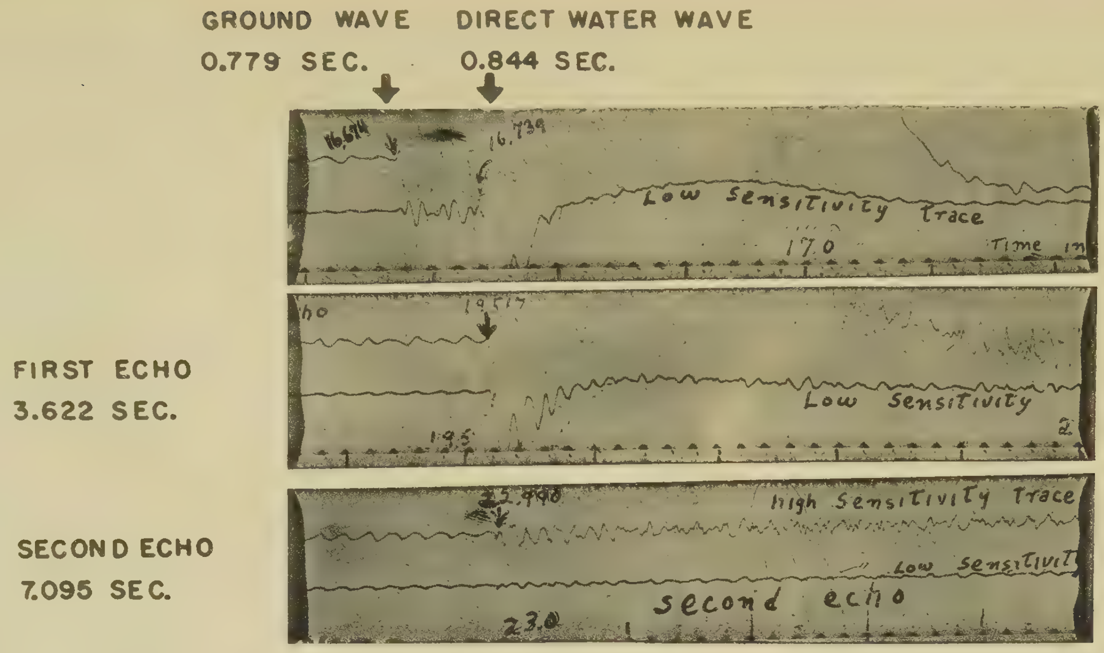
(a) Method of taking a bottom sample. (b) Underway bottom sampler

PHOTOGRAPHY OF THE OCEAN BOTTOM

GENERAL STATEMENT

During the war, the methods of underwater photography previously developed at the Woods Hole Oceanographic Institution have been applied to several military problems, most of which are not of geologic interest. The war-time activity has resulted in an increase in the number of cameras and trained operators available, in minor improvements in instruments and operating techniques, and has produced about 100 useful photographs of the bottom.

Although various types of under-water cameras have been used, the most common type was mounted on a wooden pole, about 10 feet in length, weighted at the bottom to keep it erect. Thus, when the camera was lowered on floats or on a line, it always pointed downward. A trigger weight was suspended below the camera at the distance for which the camera was focused. When the trigger weight struck bottom, the shutter was tripped, and a flash bulb fired (Fig. 11).



DEEP SEISMIC STATION 1460 FATHOMS

140 MILES SOUTH OF CAPE COD, MASS.

25 JULY 1940 LAT. 39°21'N LONG. 70°40'W

SEISMOGRAMS FROM DEEP SEISMIC MEASUREMENTS
July 25, 1940, 1460 fm., 39°21′ N., 70°40′ W.

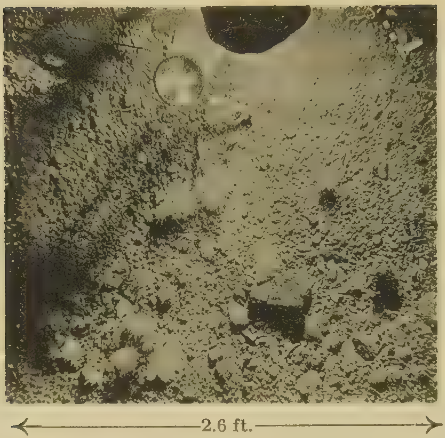


FIGURE 1. STONY BOTTOM.
Position: 42°09′N., 66°30′ W., depth: 324 ft., date: 6/24/40, camera to bottom: 7.1 ft.

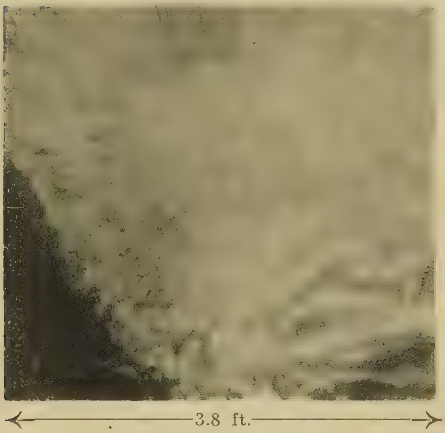


FIGURE 2. ROCK BOTTOM.
Position: 41°18′ N., 70°51.4′ W., depth: 36 ft., date: 9/1/42, camera to bottom: 4 ft.

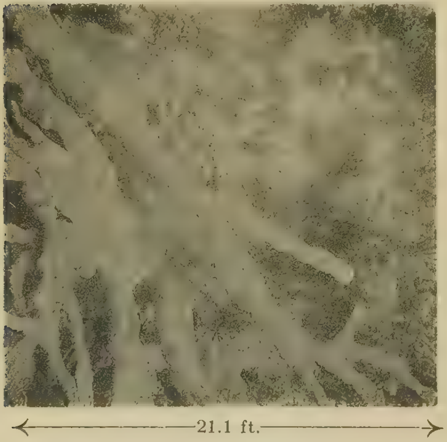


FIGURE 3. CORAL BOTTOM.
Position: 24°56′ N., 76°08′ W., depth: 36 ft., date: 8/11/43, camera to bottom: 12 ft.

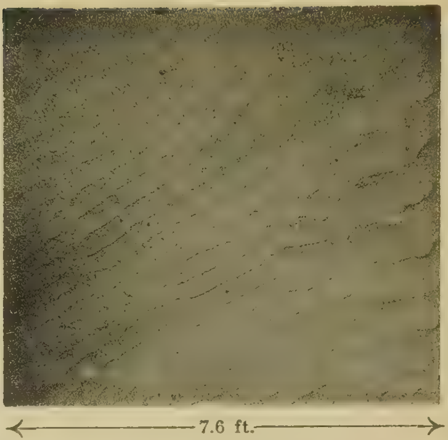


FIGURE 4. SAND RIPPLES.
Position: 34°41.5′N., 75°35.1′W., depth: 390 ft., date: 8/11/42, camera to bottom: 12 ft.

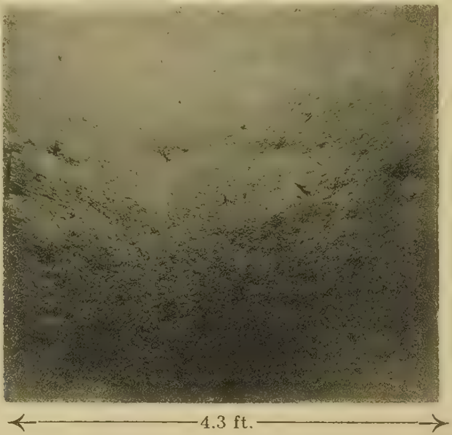


FIGURE 5. MUD BOTTOM.
Position: 40°09′ N., 71°22′ W., depth: 300 ft., date: 10/9/41, camera to bottom: 7 ft.

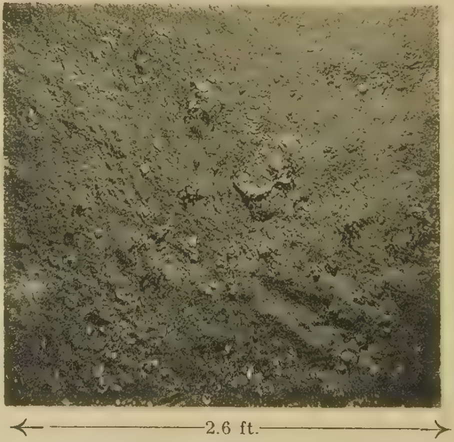


FIGURE 6. SAND-MUD BOTTOM.
Position: 40°41′ N., 67°02′ W., depth: 432 ft. date: 6/21/40, camera to bottom: 7.1 ft.

PHOTOGRAPHS OF TYPES OF OCEAN BOTTOMS

GEOLOGICAL INFORMATION FROM UNDER-WATER PHOTOGRAPHS

The type of geological information given by photographs of the bottom can best be illustrated by typical pictures.

The general type of bottom, such as rocky, stony, coral, sand, or mud is the most important and most easily recognized feature (Pl. 8).

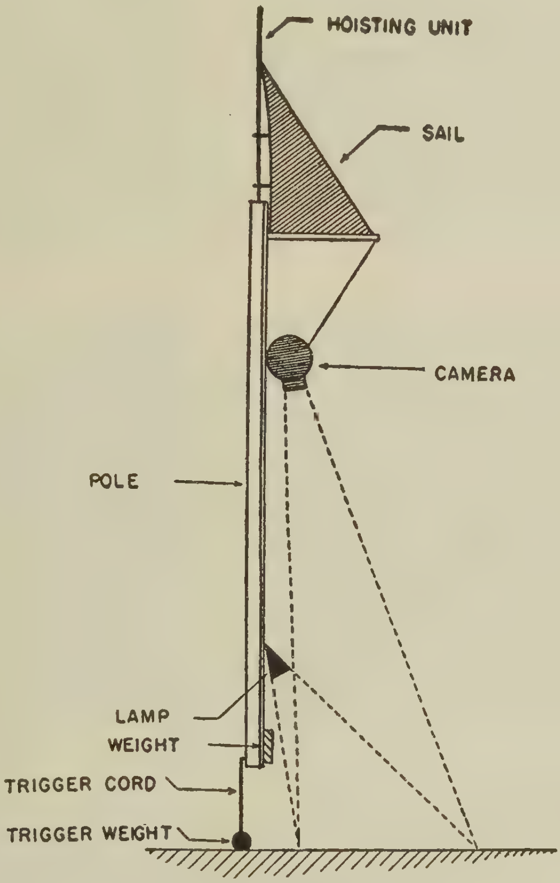


Figure 11.—*Schematic diagram of under-water camera*

As these photographs cover from 10 to 1000 square feet of bottom, they give a much truer picture of conditions than a single bottom sample. For example, in a small area near Boston Lightship where numerous bottom samples had shown only mud, a bottom photograph showed the contact between a stony area and a rocky area, both covered with a thin layer of mud (Pl. 9, fig. 4).

Physical peculiarities of the bottom that would be missed by other methods are shown by photographs. For example, various types of sand ripples are shown in Figures 5 and 6 of Plate 9.

An estimate of the compaction of the bottom can often be made from the depth to which the trigger weight sinks into bottom or from the size of the silt cloud sometimes formed when the trigger weight strikes. The latter is plainly shown in Figure 1 of Plate 9.

The concentration of marine organisms or of shells over an area of the bottom can be determined. Various concentrations of marine life are illustrated in Plate 10.

LONG-RANGE SOUND TRANSMISSION IN THE OCEANS

GENERAL STATEMENT

By taking advantage of the refractive properties of the water it has been possible to transmit acoustical signals through the water to distances which vastly exceed anything previously thought possible. Recently, a small bomb dropped off Dakar in Africa was heard on Eleuthera Island in the Bahamas—about 3100 miles away. No other man-made sound has been heard at more than a small fraction of this distance.

REFRACTION EFFECTS

An examination of the thermal structure (Fig. 12) of North Atlantic water at typical stations shows that the temperature decreases rapidly from the surface to a depth of about 4000 feet and then remains relatively constant to bottom. As a result (Fig. 13) the velocity of propagation of sound decreases, due to the temperature decrease, from surface to 4000 feet and then increases, due to the pressure increase, from there to bottom. This type of velocity pattern is known as a sound channel and may be used to great advantage in sound transmission. The depth of minimum sound velocity is known as the axis of the sound channel.

When sound travels in a medium in which the velocity changes with depth, the sound rays are refracted according to Snell's Law. In the present case, theyare bent downward above the axis of the sound channel and upward below the axis. Sound rays may be bent back and forth across the depth of minimum velocity so that they may travel to very great distances without reflection from surface or bottom. A calculation has been made to determine the paths of rays from a sound source located at the sound-channel axis. (*See* Pl. 11.) It is found that all rays having initial inclinations less than about 12° are sufficiently refracted that they never encounter surface or bottom. Such rays are known as sound-channel rays. The effect of the sound channel may be compared to that of a speaking tube.

SIGNAL STRUCTURE

Plate 11 shows that there are many different rays along which the sound may reach a distant receiver located on the axis of the sound channel. Those rays with large initial inclinations reach almost to surface and bottom on each oscillation and make relatively few oscillations across the axis of the channel. The rays with small initial inclinations make many small oscillations and remain relativel ynear the axis.

Although those rays which remain near the sound-channel axis have a slightly shorter actual path to travel, they are the last to arrive at a given point because

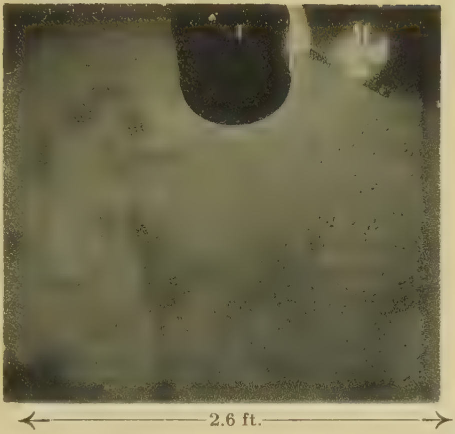


Figure 1. Soft Bottom.
Position: 40°31′ N., 67°35′ W., depth: 438 ft.,
date: 6/21/40, camera to bottom: 7.1 ft.

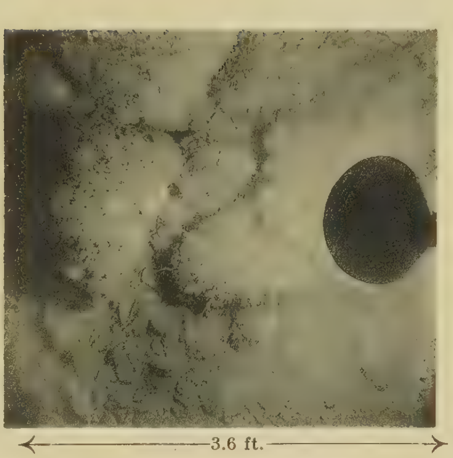


Figure 4. Composite Bottom.
Position: 42°23′ N., 70°44′ W., depth: 96 ft.,
date: 8/1/45, camera to bottom: 5.8 ft.

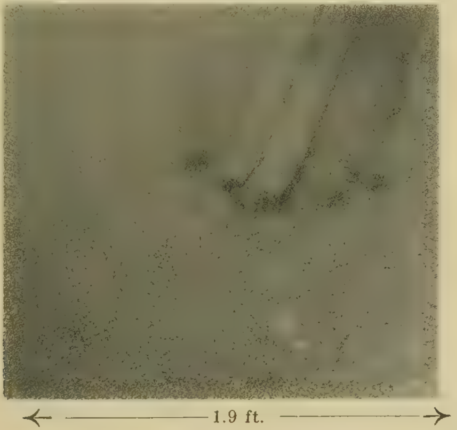


Figure 2. Firm Bottom.
Position: 41°12′ N., 72°33′ W., depth: 60 ft.,
date: 9/2/42, camera to bottom: 4 ft.

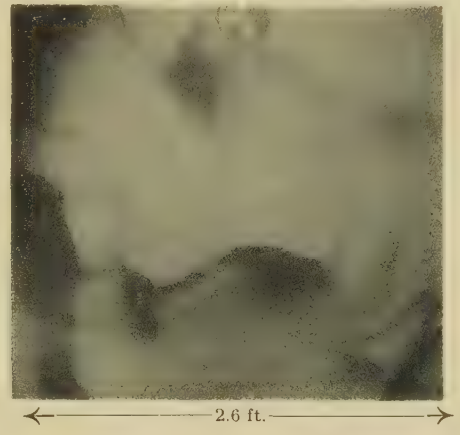


Figure 5. Sand Ripples.
Position: 41°55′ N., 66°47′ W., depth: 222 ft.,
date: 6/24/40, camera to bottom: 7.1 ft.

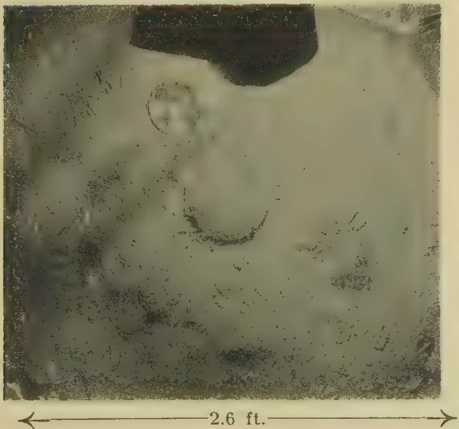


Figure 3. Composite Bottom.
Position 42°08′ N., 67°12′ W., depth: 384 ft.,
date: 6/25/40, camera to bottom: 7.1 ft.

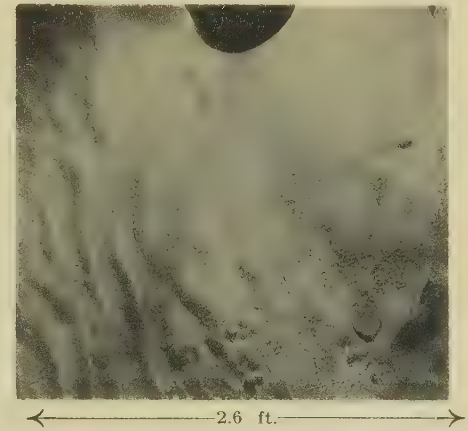


Figure 6. Sand Ripples.
Position: 41°06′ N., 67°25′ W., depth: 192 ft.,
date: 6/25/40, camera to bottom: 7.1 ft.

PHOTOGRAPHS SHOWING COMPACTION, COMPOSITE BOTTOMS,
AND SAND RIPPLES

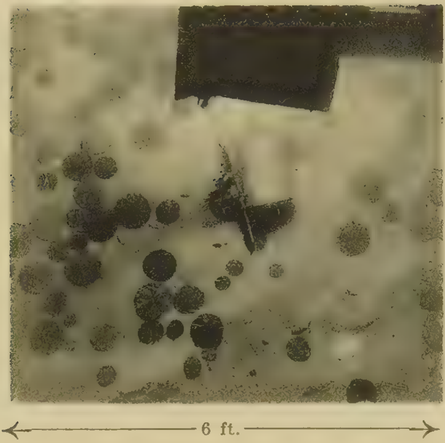


FIGURE 1. SAND DOLLARS.
Position: 43°28′ N., 70°06′ W., depth: 60 ft.,
date: 3/21/42, camera to bottom: 8 ft.

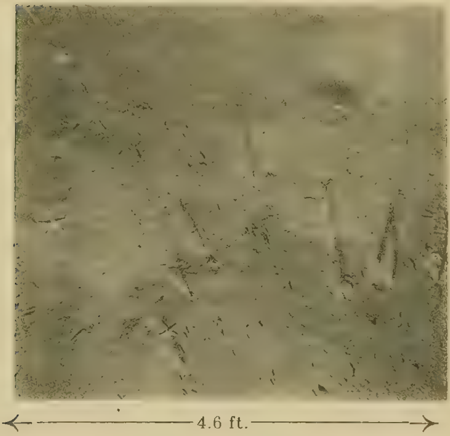


FIGURE 2. SEA PENS.
Position: 40°09′ N., 71°22′ W., depth: 300 ft.,
date: 10/9/41, camera to bottom: 7 ft.

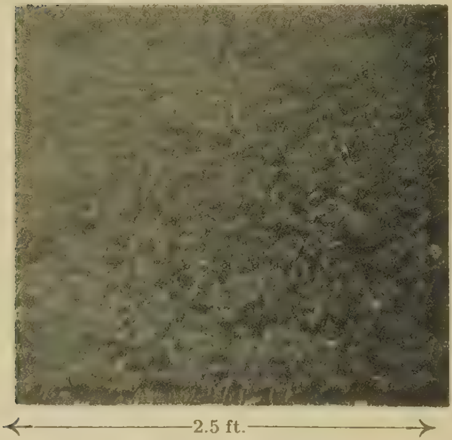


FIGURE 3. MUSSEL BED.
Position: 41°31′ N., 70°39′ W., depth: 36 ft.,
date: 10/23/42, camera to bottom: 4 ft.

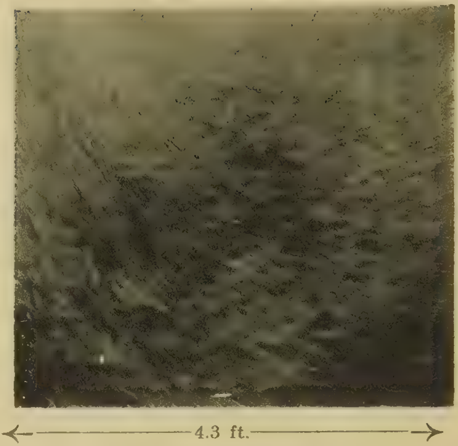


FIGURE 4. STAR FISH COLONY.
Position: 41°15′ N., 71°57′ W., depth: 110 ft.,
date: 5/10/42, camera to bottom: 7 ft.

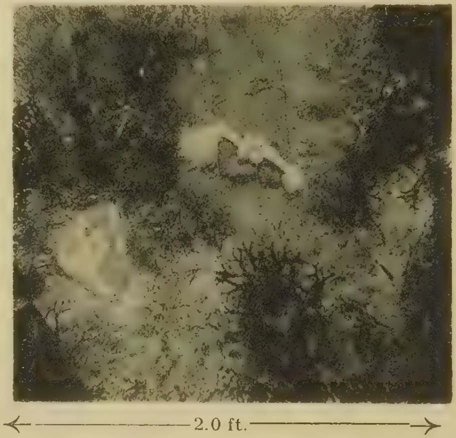


FIGURE 5. BOTTOM GROWTH.
Position: 40°24′ N., 71°05′ W., depth: 18 ft.,
date: 9/3/42, camera to bottom: 4 ft.

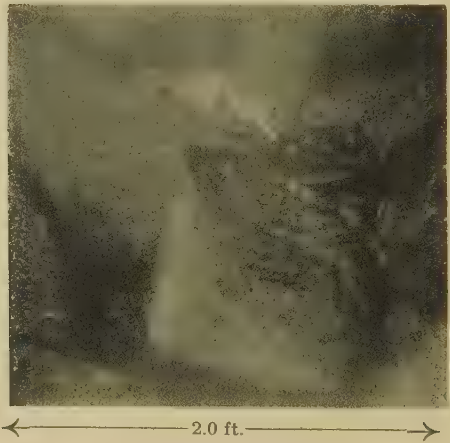


FIGURE 6. BOTTOM GROWTH.
Position: 41°21′ N., 71° 04′W., depth: 30 ft.,
date: 9/3/42, camera to bottom: 4 ft.

PHOTOGRAPHS OF PLANT AND ANIMAL LIFE ON THE SEA FLOOR

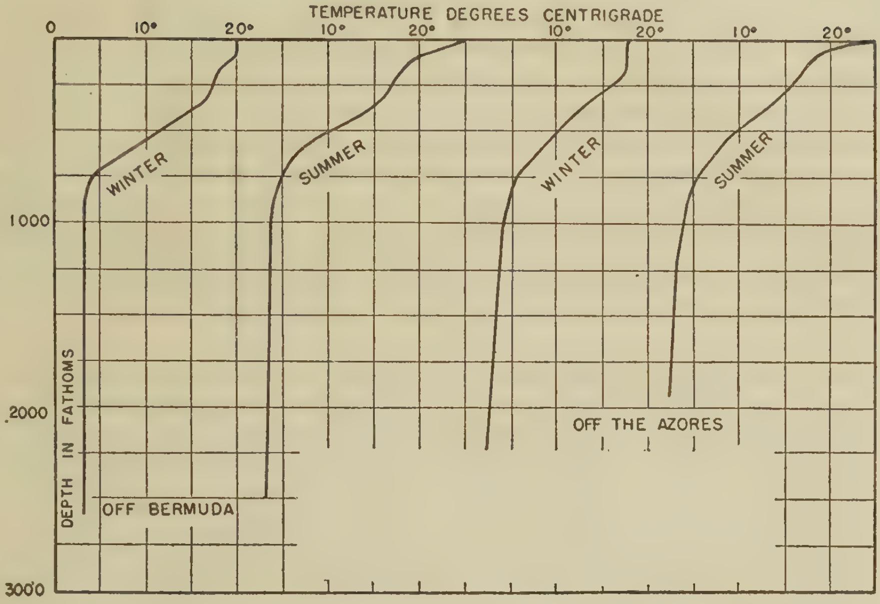


Figure 12.—*Typical temperature-depth curves in the North Atlantic ocean*

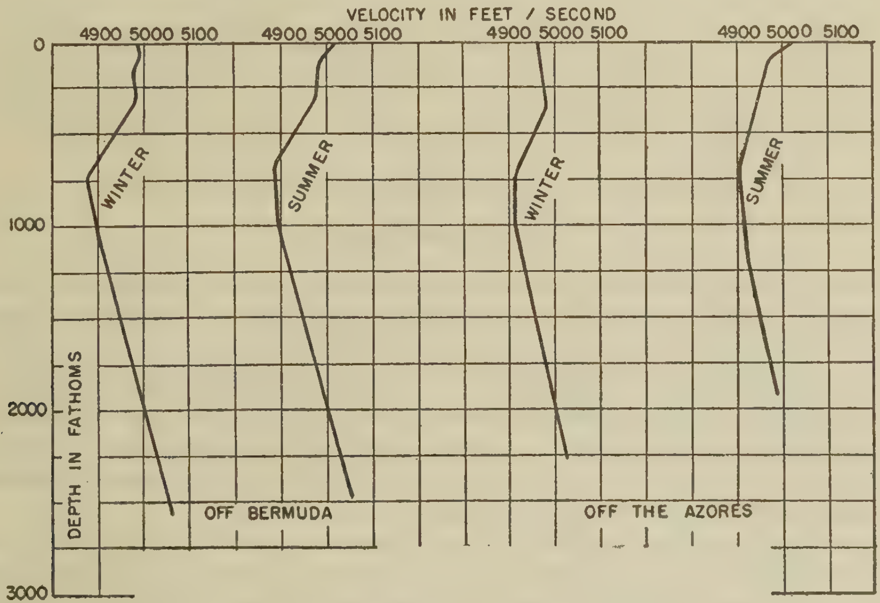


Figure 13.—*Typical velocity-depth curves in the North Atlantic ocean*

their entire path lies near the depth of minimum sound velocity. Calculation shows that the mean or effective velocity varies from 4890 feet per second for the axial rays to 4960 feet per second for those rays which reach practically to the surface.

This is a variation of about 1 per cent. If we consider as an example a shot at a distance of 1000 miles, the travel time is about 20 minutes. This difference in velocity causes an explosion sound to spread out into a signal whose duration is about 12 seconds at 1000 miles. As a result, the signal has a highly recognizable pattern (Fig. 14). It sounds like kettle drums, starting very gradually and faintly. The tempo and the intensity both increase to the very end of the signal, which is an abrupt cut-off from maximum intensity to complete silence. This abrupt cut-off is useful because it is a sharp feature whose arrival can be timed to better than 1/10 second. This feature is well illustrated in Plate 12, an actual record for a shot at 300 miles.

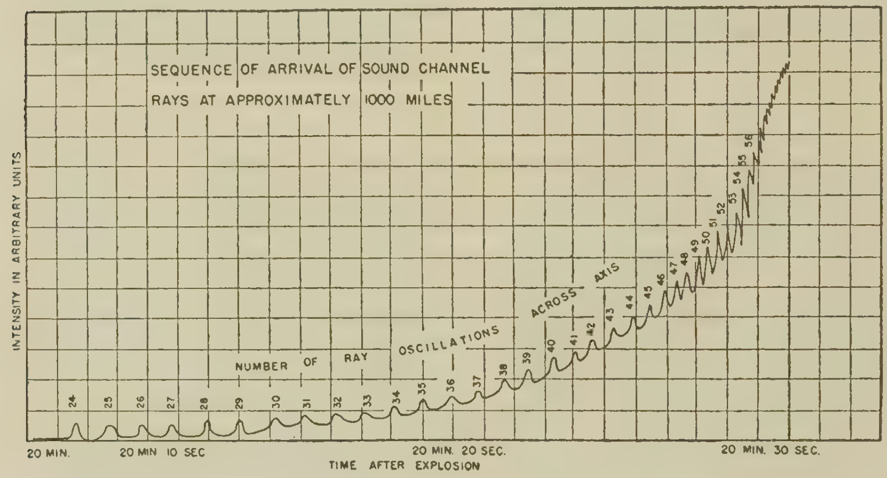


FIGURE 14.—*Sequence of arrival of sound channel rays at approximately 1000 miles*

PRACTICAL APPLICATIONS

The means for generating and receiving signals have been reduced to reasonable simplicity. A bomb which explodes hydrostatically at the axis depth can be made for a few dollars. The signals have been received on shipboard by lowering the hydrophone to the sound-channel axis and at a shore installation by leading a cable from the beach to this depth. The shore-based installation is far more reliable for operation in all types of weather. Signals received at shore-based stations are somewhat complicated by reflections from the sloping bottom, but the essential features remain, and the signals are perfectly satisfactory.

Three major geologic applications to sound-channel transmission have been considered: position fixing, submarine volcano location, and discovery of shoal areas. Reception at two receiving stations whose positions are known will provide a fix of the sound source, provided the time of the explosion is known accurately. Reception at three stations provides a fix and also gives the time of the explosion. These fixes are accurate to about a mile, and in all probability the error can be reduced. Here we

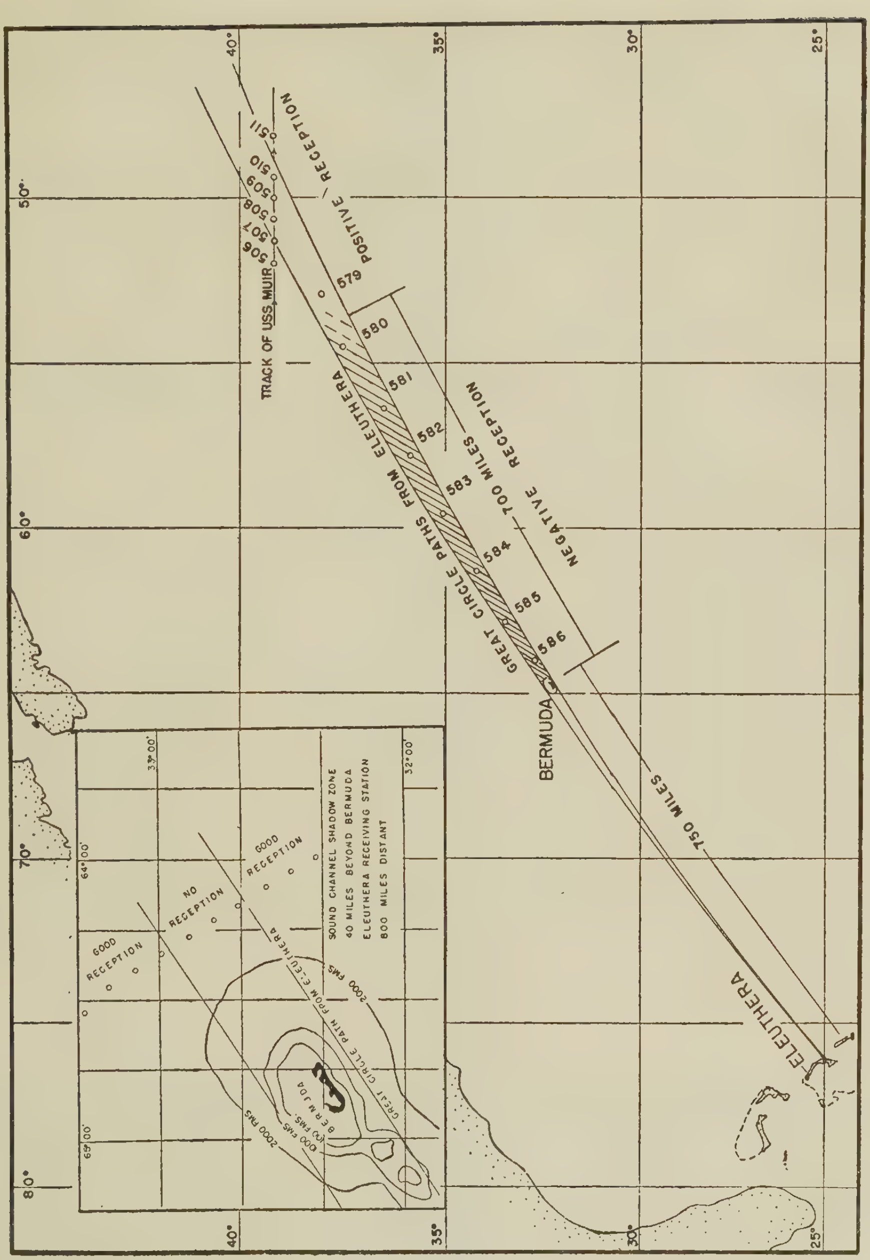

40°
35°
30°
25°
50°
60°
70°
80°
TRACK OF USS MUIR
506
507
508
509
510
511
POSITIVE — RECEPTION
579
580
581
582
583
584
585
586
GREAT CIRCLE PATHS FROM ELEUTHERA
NEGATIVE — 700 MILES — RECEPTION
BERMUDA
750 MILES
ELEUTHERA
37°00'
32°00'
64°00'
65°00'
GOOD RECEPTION
NO RECEPTION
GOOD RECEPTION
SOUND CHANNEL SHADOW ZONE
40 MILES BEYOND BERMUDA
ELEUTHERA RECEIVING STATION
800 MILES DISTANT
2000 FMS
GREAT CIRCLE PATH FROM ELEUTHERA
BERMUDA
100 FMS.
1000 FMS
2000 FMS

FIGURE 15.—*Shadow zone at Eleuthera for Bermuda Island*

have a system of location that is effective over thousands of miles and can bring to all branches of geophysical work on the high seas the advantages which Radio Acoustic Ranging has brought to the U. S. Coast and Geodetic Survey (Adams, 1942) in its work on the continental shelves.

The value of this system for rescue at sea is great, since any life boat or raft can carry a bomb with which a distress signal, automatically giving a fix of position, may be transmitted. It is to be hoped that the life-saving application will result in a world-wide network of receiving stations which will give valuable geological data as a byproduct.

Some sounds have been heard on the single installation now in operation[2] which are believed to originate in submarine volcanic activity. There can be no check on the location of the source of these sounds until a network of listening stations is available, but it is highly probable that submarine eruptions may be heard and their positions plotted once a listening system is in existence.

The use of sound-channel transmission for discovering shoal areas is a promising application. These signals travel great-circle paths, and they require that these paths be clear of obstruction to a depth of the order of 4000 feet.

An experiment was made to map the acoustical shadow cast by the Bermuda Platform (Fig. 15). Bombs dropped along the center line of the shadow zone gave negative reception to 700 miles and were heard faintly beyond this distance. At 900 miles from Bermuda, and 1650 miles from the receiving station at Eleuthera, bombs were dropped at close spacing along a line which crossed the shadow zone. Those near the center of the shadow zone were just barely heard, while those outside it were heard with normal intensity for that range. A traverse across the shadow zone 40 miles beyond the island showed a sharp shadow zone of the expected width.

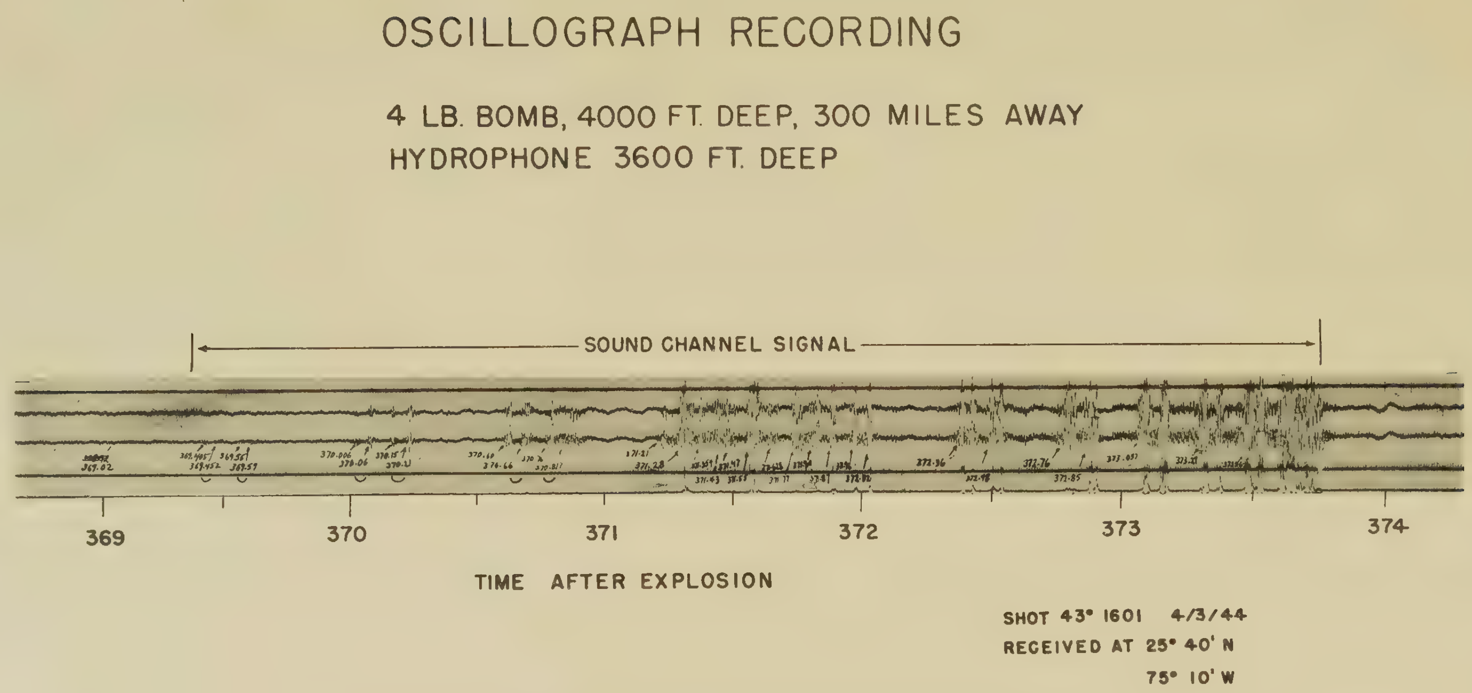
This experiment shows the effectiveness of this method for searching large areas for the presence of shoals. An area can be scanned at the rate of several thousand square miles per hour. By using several listening stations cross bearings on these shoals would locate them so closely that they could be readily explored with a fathometer.

CONCLUSIONS

Seismic measurements in the shallow water along the western margins of the Atlantic Ocean have been made at various locations. The depths to basement determined at these locations were 3050 feet at Solomons Shoal, 2950 feet at Solomons Deep, 6250 feet at Jacksonville Shoal, 7600 feet at Jacksonville Deep, 1300 feet at Virgin Islands Shoal, 2700 feet at Virgin Islands Deep, greater than 17,000 feet at Barbados, 12,200 feet at the Gulf of Paria, and 22,700 feet at the mouth of the Orinoco River. The values at Jacksonville and Solomons are in reasonable agreement with the best available well data. No well data were available at the other stations.

Multiple sound waves from the oscillations of the gas bubble resulting from an explosion may lead to confusion in interpreting seismic records. These oscillations may be avoided by placing the charge above a critical depth.

[2] Installation abandoned December, 1945, Navy orders.



SEISMOGRAM OF SOUND-CHANNEL TRANSMISSION AT 300 MILES
4 lb. bomb; bomb depth 4000 ft.; hydrophone depth 3600 ft.

Frequency dispersion in shallow water was noted. This phenomenon may be used to determine the properties of the bottom to a depth approximately equal to the water depth. It is believed that this phenomenon can be used in deep-water investigations.

Deep-water seismic observations were made with equipment lowered by cables and by floats. Analysis of surface echoes makes it possible to determine the relative times without other communication at all recording units.

Two stations occupied in 1500 fathoms and one in 2600 fathoms showed the surface layer of the bottom to have approximately the same sound velocity as the weathered surface layer on land. The records indicate that sediments are more than 600, 1200, and 1500 feet thick at these stations.

Using a new method, the ocean bottom may be sampled from ships underway at speeds up to 8 knots. More accurate location of the source of samples is possible, and a greater area may be sampled in the same time than with other instruments. A depth recorder has been used by a simple addition to the instrument so that the depth at which the sample was taken could be determined.

A bathymetric chart of the offshore slope on the Atlantic side of Eleuthera Island, Bahamas, was obtained. Two profiles of submarine canyons show that they are deeper and more precipitous than canyons along the east and west coasts of the United States.

The use of under-water photography is an aid in geological observations of bottom materials, sand ripples, compaction of sediments, and distribution of life.

Long-range sound transmission was found in the natural sound channel of the oceans. Utilizing this feature, the sound from a 6-pound TNT bomb was heard at ranges as great as 3100 miles. The interference of an island structure, such as Bermuda, between the shot and the receiver was observed. Certain noises which have been heard while monitoring for shots are tentatively attributed to submarine volcanic activity. Three receiving stations may be used to locate a bomb with an accuracy of about a mile.

A network of stations will probably be set up to utilize the life-saving applications of this system. It is hoped that the useful geologic applications of position finding for survey vessels, location of shoals by scanning methods, and location of submarine volcanic activity may be available as byproducts.

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Contribution No. 352

PHYTOPLANKTON-ZOOPLANKTON RELATIONSHIPS ON GEORGES BANK[1]

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INTRODUCTION

Comparisons of different oceanic regions often suggest that in the largest sense there is a direct relationship between phytoplankton and zooplankton—that is, banks and coastal areas with large concentrations of phytoplankton are likely to be rich in zooplankton, while sparser crops of both occur in deep oceanic waters. On the other hand, surveys of particular areas often show an inverse relationship, with local swarms of zooplankton occurring in phytoplankton-poor waters, alternating with dense patches of phytoplankton containing few animals. Harvey, Cooper, LeBour and Russell (1935) explained the inverse relationship observed in the English Channel as a grazing phenomenon, while Hardy and Gunther (1935) advanced the theory of animal exclusion, which postulated avoidance of phytoplankton patches by the animals. Steemann Nielsen (1937) and Clarke (1939) elaborated the theory of the grazing phenomenon with particular emphasis on the time factor, pointing out that the presence of a swarm of adult copepods is the result of weeks of growth and is dependent on the quantity of phytoplankton available throughout the growth period. Thus, as described by Marshall, Nicholls and Orr (1934), it is possible for such a swarm to pass successfully through its developmental stages at the same time as (and possibly as a direct result of) a diatom flowering. In such a case two relationships between phytoplankton and zooplankton might be described: (1) a direct correlation between a diatom flowering and the swarm of copepods to which it eventually gives rise, and (2) an inverse relation obtained by comparing an area in which the zooplankton eventually grazes the phytoplankton to a low level with other localities in which this has not occurred.

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OBSERVATIONS ON GEORGES BANK

Fig. 11A shows the mean total phytoplankton and zooplankton populations of Georges Bank as determined during cruises made in 1939 and 1940 (Clarke, Pierce and Bumpus, 1943; Riley, 1941). The seasonal cycles are similar to those in numerous other localities, with spring phytoplankton and summer zooplankton maxima, mid-winter minima for both, and a gradual upward trend in the zooplankton population during the development of the spring diatom flowering; these are followed by a sharp increase in the number of animals in late April and early May, coincident with the decline of the diatom burst. Thus the seasonal trend in the phytoplankton-zooplankton relationship is direct in the early spring and inverse later.

Analysis of individual station records reveals that the horizontal distribution of plant and animal plankton varied from one month to the next in a way that reflected the general seasonal trend. During March, areas in which the spring diatom flowering was beginning were also foci of zooplankton increase. In May, on the other hand, there was little zooplankton in areas of diatom abundance, the latter being sparse in places where zooplankton growth had attained large proportions. Correlations were prepared showing the relationship between the horizontal distribution of phytoplankton and zooplankton on each of the cruises. These are plotted in Fig. 11B. They show clearly the moderately high direct relationship in March and the highly significant inverse relation in May. During the other cruises the correlations were statistically insignificant.

Further facts of interest in this connection are revealed by examination of the seasonal cycles and horizontal distribution of individual species and genera of zooplankton. Fig. 12 shows the cycles of eight of the more important groups and their correlations with total phytoplankton. Seasonal minima were generally accompanied by zero or positive correlations, and in most cases there was a positive correlation at the time when the species was beginning to increase. In each case there was a negative correlation with phytoplankton at the time when the species reached its seasonal peak. All these correlations were either statistically significant or significantly different from the preceding positive correlation, except in the case of Centropages, for which no preceding data are available. Animals such as decapod nauplii and *Pseudocalanus minutus*, which developed a peak population slowly, also showed a slowly declining correlation with phytoplankton, while in other groups both changes were more rapid. Thus, it is evident that individual zooplankton groups showed relationships with phytoplankton in their horizontal distribution that were similar to

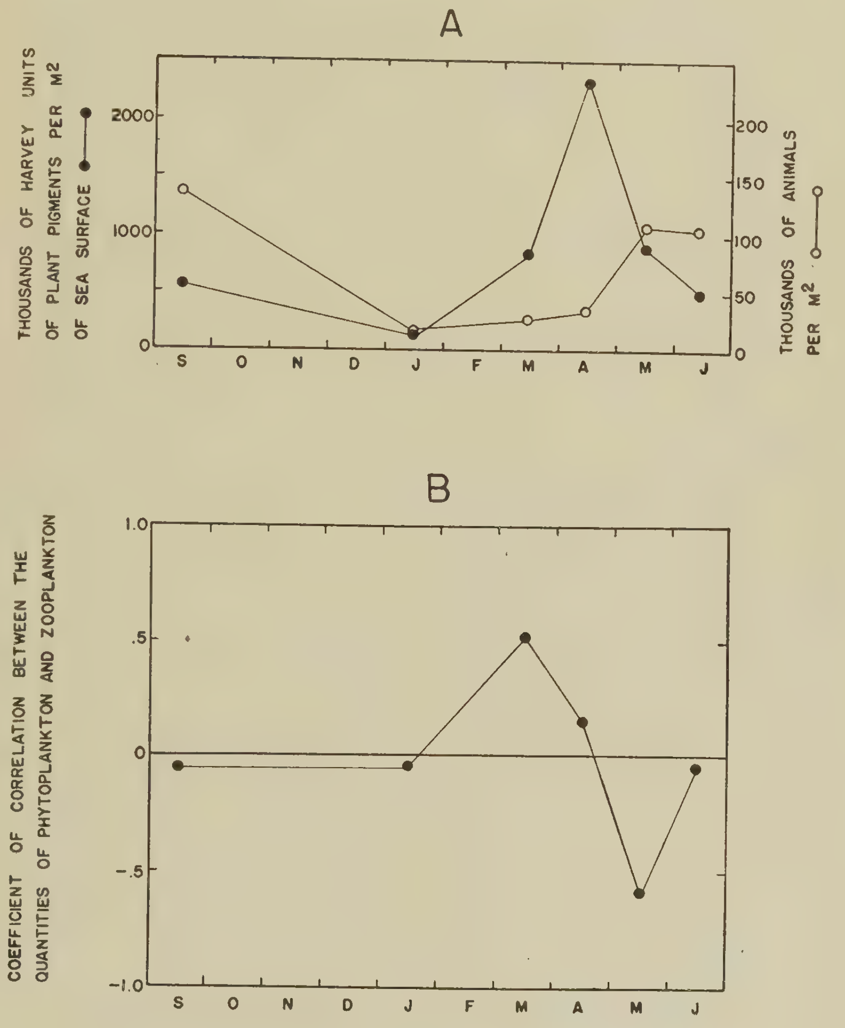
A
THOUSANDS OF HARVEY UNITS OF PLANT PIGMENTS PER M2 OF SEA SURFACE
2000
1000
0
200
150
100
50
0
THOUSANDS OF ANIMALS PER M2
S
O
N
D
J
F
M
A
M
J
B
COEFFICIENT OF CORRELATION BETWEEN THE QUANTITIES OF PHYTOPLANKTON AND ZOOPLANKTON
1.0
.5
0
-.5
-1.0
S
O
N
D
J
F
M
A
M
J

Figure 11.

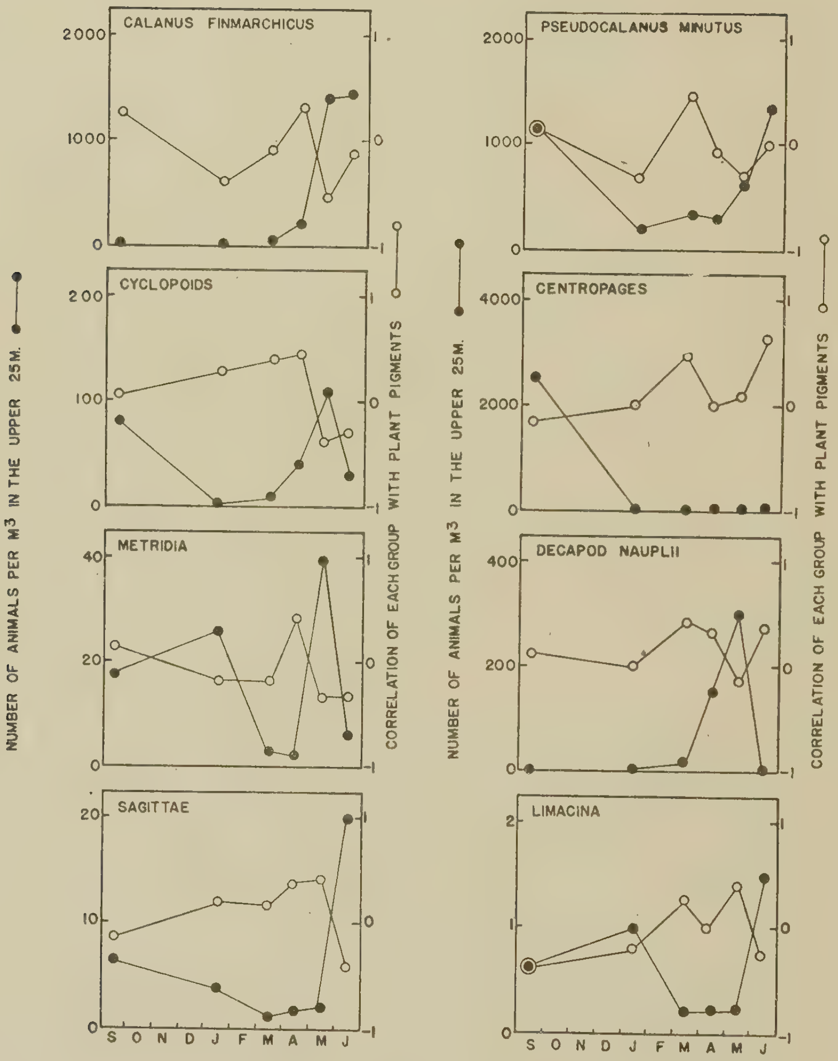
CALANUS FINMARCHICUS
PSEUDOCALANUS MINUTUS
CYCLOPOIDS
CENTROPAGES
METRIDIA
DECAPOD NAUPLII
SAGITTAE
LIMACINA
NUMBER OF ANIMALS PER M3 IN THE UPPER 25M.
CORRELATION OF EACH GROUP WITH PLANT PIGMENTS
S O N D J F M A M J
2000
1000
0
200
100
40
20
10
4000
400
2
1
-1

Figure 12.

those of the total population, and this is particularly significant in that their seasonal peaks appeared at different seasons of the year.

In any problem as complex as plankton relationships there may be some doubt as to the significance of a simple correlation between two groups of organisms, because obviously many other factors can affect their relationship. For example, it is not impossible that variations in temperature might affect both plants and animals in such a way as to produce a significant phytoplankton-zooplankton correlation. Such a situation could be detected, however, by calculating the partial correlation between phytoplankton and zooplankton in respect to temperature.

The statistical method of partial correlations makes allowance for indirect relationships by correcting the correlation between the two main variables on the basis of their relation with the third variable, which is suspected of indirect influence. By an elaboration of the method it is possible to eliminate simultaneously the effects of a number of indirect factors. The only limitation of the technique is the practical difficulty that in such a complex system as the natural environment it is hardly possible to obtain measurements of all the factors that might be important. Therefore such an analysis is only an approximation to the true relationship.

In the present analysis the two factors most likely to have indirect influence are temperature and depth, the latter because stations were made on various parts of the Bank, some of which extended into fairly deep water at its edge, and because important relationships had been noted previously between the depth of water and both the quantity of plankton and the distribution of species. Therefore, these two factors were taken into account in deriving the partial correlations, together with phosphate and nitrate content of the water, which might conceivably have indirect effects. The resulting partial correlation was −.510 in May, which was nearly the same as the simple correlation. The correlations for September, January, and June were changed slightly (−.170, .089, and −.200 respectively). The positive correlation observed in March was reduced to an insignificantly low level (−.015), and the slight positive April correlation was changed to a somewhat stronger negative one (−.246). Thus the direct relation between phytoplankton and zooplankton in the early spring can be explained as the product of other factors of the environment, but there is nothing in the available data that denies the biological significance of the negative correlation observed in May.

DISCUSSION

Negative Phytoplankton-Zooplankton Correlation and Grazing Effect. It is apparent that the plant-animal relationship on Georges Bank is similar to that observed in many other regions in the springtime and therefore might be described as a grazing or animal exclusion phenomenon. There are two reasons, however, for believing that the latter cannot be applied in this particular case. First, the vertical distribution of phytoplankton on Georges Bank was too nearly constant to favor the method of avoidance by vertical migration postulated by Hardy. Second, the time of greatest negative correlation varied from one species to another. It apparently had nothing to do with the richness of the phytoplankton crop which supposedly sets up the avoidance reaction. Rather, the negative correlation, both in total zooplankton and in individual species, was greatest when the zooplankton reached its peak, irrespective of the quantity of phytoplankton in the water at that time. This points to the grazing phenomenon as the cause of the relationship.

The quantitative aspects of the relationship are further elaborated in Tables I and II. The first two columns of Table I show the average values for phytoplankton and zooplankton during each cruise. The values for phytoplankton were determined according to the Harvey plant-pigment method and are listed as thousands of "Harvey units" per m². The partial correlations are used to calculate regression equations for the phytoplankton-zooplankton relationship. By this means a quantitative estimate of grazing is derived from the observed negative correlations, and the constants for the regression equations are listed in the third column in terms of phytoplankton (Harvey units x 1000) consumed per 1000 animals. The product of the constants and the mean quantity of animals is an estimate of the total amount of grazing during the time required to develop the correlation,

TABLE I. Mean Quantities of Plankton on Georges Bank and Estimates of the Grazing Phenomenon

Month	*Mean plant pigments*	*Mean number of animals per m²*	*Estimate of plant pigment consumption per 1000 animals*	*Estimated total consumption*	*Mean phytoplankton crop and grazing estimate*
Sept.	560	135,000	0.26	35	595
Jan.	120	14,000	−0.47	−7	113
Mar.	830	24,000	0.62	15	845
Apr.	2,300	32,000	5.3	170	2,470
May	870	106,000	3.5	371	1,241
June	480	103,000	0.55	56	536

and this is shown in column 4. The sum of columns 1 and 4 suggests what the phytoplankton would be if no animals were present.

The relationship between phytoplankton and zooplankton can be understood more clearly if an attempt is made to convert the estimates into directly comparable terms. This is done in Table II. Figures for zooplankton volume (column 1) were determined by the displacement method. The second column was derived on the assumption that the dry weight of organic matter in the zooplankton averages 25% of the volume in cubic centimeters. The phytoplankton figures in the third column are based on measurements from a previous paper (Riley, 1941) which gave a conversion factor of 35 mgs. of dry organic matter per thousand units of plant pigments. The fourth column utilizes the same factor together with data from Table I to determine the weight of phytoplankton consumed during the course of development of the observed correlation between phytoplankton and zooplankton. Finally, the last two columns list the data on consumption as percentages of the plant and animal weights.

TABLE II. Quantitative Comparisons of Phytoplankton and Zooplankton

Month	*Zooplankton volume cc/m²*	*Dry weight of zooplankton g/m²*	*Dry weight of phytoplankton g/m²*	*Estimated total consumption g/m²*	*Per cent of phytoplankton crop consumed*	*Food requirement, % of zooplankton weight*
Sept.	38.1	9.5	19.6	1.2	6	13
Jan.	11.1	2.8	4.2	−0.2	−5	−7
Mar.	58.2	14.5	29.0	0.5	2	3
Apr.	81.3	20.3	80.5	6.0	7	30
May	152.6	38.1	30.4	13.0	43	34
June	60.1	15.0	16.8	2.0	12	13

The gradual development of the negative correlation during the spring months might suggest a static situation in which a swarm of zooplankton developed in a particular local water mass and gradually reduced the phytoplankton crop during a period of two or three months. However, reference to Table II indicates that this is very unlikely since the increment in the weight of zooplankton during the spring months exceeded the estimated total consumption. Moreover, the values in the last column of Table II for April and May are of the same order of magnitude as the estimate made by Harvey and his associates (1935) for one day's consumption at the height of the diatom flowering, while the estimates for other months are similar to the minimum requirements for one day determined by Marshall, Nicholls and Orr (1935) from a study of the respiration of *Calanus finmarchicus*.

In this connection it can be seen in Table II that between the April and May cruises, when the zooplankton was increasing most rapidly, the mean phytoplankton crop decreased about 50 g. per m^2, although experiments on Georges Bank plankton (Riley, 1941) showed that the photosynthetic rate was increasing rather than decreasing during this period. The total difference between the experimentally estimated phytoplankton production and the observed crop was about 80 g. per m^2, most of which probably was due to grazing, although perhaps some of it can be ascribed to death by other causes. Therefore, the total consumption may have been more than ten times as great as the increase in the phytoplankton-zooplankton correlation during the same period would indicate. Thus it is desirable to attempt to evaluate the grazing rate more carefully by considering all the factors involved and by trying to decide whether there is good reason for the discrepancy that appears to exist.

Other Factors Involved in the Grazing Phenomenon. The maximum grazing rate can be estimated by methods similar to those described by Fleming (1939), who suggested the equation

$$\frac{\Delta P}{\Delta t} = P\,[a - (b + ct)], \tag{1}$$

in which the change in the diatom population in respect to time is dependent on a, the rate of multiplication of the population, b, the initial grazing rate, and c, the change in the grazing rate due to changes in zooplankton population. The validity of the equation depends on the assumptions that the rate of multiplication of phytoplankton is constant, that an animal grazes a fixed proportion of the diatoms (filters a unit volume of water) per day, that there is no loss other than by grazing, and that the effects of turbulent mixing are negligible. The equation can be applied to the present study by introducing a term a_1, which represents the change in the multiplication rate with time, which is required according to the evidence from experiments on the photosynthesis of diatom populations on Georges Bank. The resulting equation is

$$\frac{\Delta P}{\Delta t} = a + a_1t - (b + ct), \tag{2}$$

and integrating,

$$P_t = P_\circ e^{t[a + \frac{1}{2} a_1 t - (b + \frac{1}{2} ct)]}, \tag{3}$$

in which $P_\circ$ is the initial population, and P_t is the population at time t. Using the equation to express the change in phytoplankton between the April and May cruises, with the experiments on photosynthesis as the basis for estimates of a and a_1, and with c expressed in terms of the change in zooplankton population,

$$ln\ 870 - ln\ 2300 = 20\ (.023) + 200\ (.0065) - 20b - 200\ (.115b)$$
$$b = .064.$$

Thus, it is estimated that the April grazing rate was 6.4% of the phytoplankton population per day, or 25% of the weight of zooplankton. In May the consumption can be shown to be 17% of the animals' weight per day. These figures are very dependent on the assumption that there was no loss of phytoplankton by any cause other than grazing. Harvey and his associates (1935) believed that in the English Channel loss of diatoms by sinking or natural death was negligible. It is not yet certain whether this conclusion is also applicable to Georges Bank. Therefore the calculated values should be regarded as maximum estimates of grazing.

But the various calculations, rough as they may be, do not leave very much doubt that the correlation represents only a part of the grazing phenomenon, and perhaps a relatively small part. Furthermore, the most obvious explanation of the situation is that the continual tendency of grazing to produce such a correlation was inhibited to a greater or lesser degree by turbulent mixing, which tended to redistribute the populations more uniformly.

Georges Bank is an area dominated by strong winds during most of the winter and spring. It has rotary tidal currents typical of offshore banks, which attain a maximum velocity of three or four knots at the surface. Much of the bank water is homogeneous in respect to temperature and salinity, as is shown in diagrams by Clarke, Pierce and Bumpus (1943). However, mixing is seldom rapid or complete enough to destroy completely the last vestiges of vertical stratification of biologically active materials (Riley, 1941). With this general picture of the hydrography of the bank, it is to be expected that there might be enough turbulent mixing to interfere with the development of plankton patchiness due to grazing.

Therefore, the examination of the data with the idea of determining how mixing would affect the distribution of the plant and animal populations is in order. In the first place it is clear that although mixing tends to level the populations, growth by geometrical progression has the opposite effect. For example, during the rapid period of increase of animals between April and May, the average population rose from 24 to 106 thousand animals per m^2, a growth rate of 5.9% per day. In April 70 thousand animals was a moderately large population (the mean plus the standard deviation). If this latter population increased at the same rate, it would number 232 thousand in May. Obviously this is a much larger numerical difference between the large and average populations, although the ratio remains constant. Actually, however, in May 183 thousand animals was a large population, judged by the same criteria. In other words, there was a large numerical increase but a reduction in the ratio. Moreover, this reduction in the ratio can be used as an index of dilution of the population by mixing, provided the growth rates were relatively uniform. According to the figures given above, mixing caused a rate of reduction of the percentage difference between a large and an average population of 2.4% per day.

Studying the effect of mixing on the diatom population is more complicated because of the number of factors involved. It is necessary to use an equation of type (3) as a basis and to elaborate it by introducing factors representing the change caused by mixing. Thus in the equation

$$P_t = P_o e^{[t(a-b) + \frac{1}{2}t^2(a_1 - c)]\,[1 - t\,(d + \frac{1}{2}\,d_1\,t)]}, \tag{4}$$

d is the initial rate of dilution of the population by mixing, and d_1 is the change in the rate with time. This is not quite the same as the procedure described for zooplankton mixing rates, but it can easily be transformed into comparable terms.

In dealing with a population of average size, it is assumed that d and d_1 are negligibly small. They have a finite value when the population is larger or smaller than average. A moderately large population, defined as the mean plus the standard deviation, was 3120 thousands of units of plant pigments in April and 1393 in May. Because of the negative phytoplankton-zooplankton correlation, the larger plant populations were accompanied by smaller animal populations, the number as determined by the regression equations being 23 thousand per m² in April and 67 thousand in May. It is assumed that the initial grazing rate was correspondingly less than the value previously determined for the average population, or $b = 23/32 \times .064 = .046$. It is also assumed that the grazing rate increased proportionally to the increase in population; that is, $c = (67 - 23)\,b/23t = .096b$. Then

$$\begin{aligned} ln\ 1393 - ln\ 3120 = \{20\,(.023 - .046) + 200\ [.0065 - .096\ (.046)]\} \\ \{(1 - 20\ (d + 10d_1)\}\ d + 10d_1 = .082. \end{aligned}$$

Thus the average rate of dilution of a moderately large plant population by mixing was 8.2% per day during the April–May period. In order to compare this figure with the previously determined rate of dilution of zooplankton by mixing, it is necessary to determine the ratio between the large and average populations, reduce it by the amount indicated for zooplankton mixing, and transcribe this figure back into terms of plant pigments. When this is done, the calculated values of d and d_1, based on the zooplankton dilution rate, are 0.0022 and 0.00014 respectively. It is apparent that there is a wide discrepancy in the two estimates. The rate of mixing of phytoplankton populations appears to be 23 times as great as that of zooplankton.

The calculations suggest alternative conclusions. (1) The importance of the grazing phenomenon may be exaggerated. If part of the decrease in phytoplankton were caused by other factors, the estimate of mixing would be altered. (2) There may actually be more or less difference in the rate of mixing of plant and animal populations. Such a difference could occur only by partial segregation of the populations, but diurnal migration provides a means by which this might be effected. The alternative conclusions will be examined in turn, although, as will be seen, it is speculatory to attempt to choose between them.

Grazing Effect versus Loss of Phytoplankton by Natural Death. Experiments with laboratory cultures of diatoms (Riley, 1943) showed that after the development of a maximum population there followed a period of decrease which appeared to be a logarithmic function of the number of cells in the culture, and which appeared to be initiated by exhaustion of available nutrients. During this period of rapid natural death a large part of the population looked debilitated and was in a state of depressed physiological activity as evidenced by a low photosynthetic rate.

Comparison of these results with the natural plankton associations of Georges Bank revealed some similarities and some differences. Many of the May diatoms appeared senile, yet the photosynthetic rate was higher than in April. Counts made on individual species after three or four days' growth in experimental bottles showed increases in some species and decreases in others. It seemed likely that each species went through a growth cycle somewhat similar to that of laboratory cultures but at different times, so that at no time was the whole plankton association in a state of decay. Nor was there any time when such nutrients as phosphate or nitrate approached exhaustion.

It seems likely therefore, that a certain amount, although probably not a major part, of the decrease in population previously ascribed to grazing was actually caused by natural death. In attempting to establish its quantitative aspects it seems reasonable to assume that the death rate was a logarithmic function of the population, as in the case of laboratory cultures. Therefore, as the simplest example of such a relationship a factor s will be introduced into equation (4), which represents the death of a fixed percentage of the population each day. At the same time it will be assumed that the rate of dilution of the phytoplankton by mixing is the same as that previously determined for zooplankton. The values for d and d_1 are, as previously stated, .0022 and .00014 respectively. Then in respect to the average population, which is not affected by mixing,

$$ln\,870 - ln\,2300 = 20\,(.023) + 200\,(.0065) - 20b - 200\,(.115b) - 20s$$

$$43b + 20s = 2.731.$$

A large population, as previously defined, takes the form

$$ln 1393 - ln\,3120 = [20\,(.023) + 200\,(.0065) - 20\,b_1 - 200\,(.096b_1) \\ - 20s]\,[1 - 20\,(.0022) - 200\,(.0014)]$$

$$39b_1 + 20s = 2.633.$$

The term b_1 in the second equation points out the fact that the grazing rates of the two populations differ by the ratios of the populations, or 32 : 23; therefore the equation may be rewritten $28b + 20s = 2.633$. Subtracting this from the equation for the average population, $b = .0065$. Thus the grazing rate in April is estimated to be about 0.5% of the diatoms per day, or 2.5% of the weight of the zooplankton. This is less than the increase in the weight of the zooplankton crop, and is therefore impossibly small. If the death rate were not constant, but accelerated or decelerated with time, it would not make any difference in the apparent value of the grazing rate. The latter would be changed only if the death rate of the large population were different from that of the average population. This seems unlikely, although there is no definite evidence on the subject. Lacking such evidence, any conclusion is speculatory. However, it seems rather likely that while some small part of the observed decrease in phytoplankton may be ascribed to natural death, no reasonable assumption about the death rate can avoid the necessity of postulating also a phytoplankton mixing rate larger than that of the zooplankton.

Diurnal Migration and Grazing. The currents on Georges Bank are of two kinds: rotary tidal currents and a residual drift. In either case the frictional effect of the bottom is such that the currents are expected to have their greatest velocity near the surface. In the case of tidal currents, not only does the velocity generally diminish toward the bottom, but also the direction of the current deviates toward the right. This is described in a paper by Sverdrup (1927). Therefore the plankton at any particular depth has a different history of past movements from the plankton above and below, and if the plankton patches are sufficiently small, it also has a different history of past associations with other populations. This, combined with vertical turbulence, facilitates the mixing of populations. The mixing effect, moreover, will be more pronounced in the case of phytoplankton, which is passively scattered through the entire water column, but less in zooplankton, which tends by vertical migration to swarm at a particular depth range and therefore to be transported by horizontal currents that are more nearly uniform in velocity and direction. Thus it is possible to conceive that zooplankton swarms might be scattered less than the diatoms by turbulent mixing, and also that the association of a group of animals with any one phytoplankton population might be relatively transitory.

This would adequately explain the evidence that the observed negative correlation between plants and animals represents only part of the total grazing effect. It might be noted also that the theory resembles Hardy's theory of animal exclusion insofar as it postulates that diurnal migration is an essential part of the plant-animal relationship. Like his hypothesis, it is applicable in any place where, within the depth range of diurnal migration, current velocity varies with depth. There the resemblance ends, since the negative correlation is postulated as a result of transitory but intensive grazing of any population encountered at random rather than an avoidance of dense patches of phytoplankton.

Unfortunately, however, the theory must remain in qualitative terms for the present. More complete data on both the currents of Georges Bank and the horizontal distribution of plankton will be required before it will be possible to attempt a final solution of grazing, mixing, and phytoplankton death rates. Further work is also required to test some of the assumptions on which the equations are based, which, although they appear reasonable at the moment, are not necessarily true. It does not seem inappropriate, however, to approach the subject in this way if by doing so the unsolved problems of plankton biology can be stated more clearly.

SUMMARY

1. There is a significant inverse relationship between the horizontal distribution of Georges Bank phytoplankton and zooplankton at the time when the latter is increasing most rapidly. This is true not only of the total zooplankton but also of several individual species and genera that were examined. The evidence points to grazing as the cause of the inverse relationship.

2. Quantitative estimates of the amount of grazing required to develop the observed negative correlation between plant and animals are of the order of 35% of the weight of the animals in May, when the most rapid increase in the animal population occurred. This, however,

did not represent the total amount of grazing that occurred during the spring period, because the increase in weight of the zooplankton was considerably larger. It is suggested that turbulent mixing tended to redistribute the populations so that the correlation was not as fully developed as it would be otherwise.

3. An attempt is made on theoretical grounds to determine rates of grazing. The maximum amount of grazing that could occur (judged by the difference between the phytoplankton production rate and the rate of change of the standing crop) was about 25% of the animals' weight per day in April and 17% in May.

4. It is estimated that the effect of turbulent mixing on zooplankton amounted to a daily reduction of about 2.4% of the percentage difference between a given population and the average population. The effect of mixing on phytoplankton appears to be very much greater.

5. The reason for the apparent difference in mixing rates cannot be absolutely established, but it appears likely that diurnal migration is involved. It is reasonable to suppose that on Georges Bank the velocity and direction of the currents vary with depth. In such a case turbulent mixing should be more effective in levelling the phytoplankton populations, which are scattered through the entire water column, than zooplankton, which tends to aggregate at particular depths.

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Contribution No. 353

FACTORS CONTROLLING PHYTOPLANKTON POPULATIONS ON GEORGES BANK[1]

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A complex field such as oceanography tends to be subject to two opposite approaches. The first is the descriptive, in which several quantities are measured simultaneously and their inter-relationships derived by some sort of statistical method. The other approach is the synthetic one, in which a few reasonable although perhaps over-simplified assumptions are laid down, these serving as a basis for mathematical derivation of relationships.

Each approach has obvious virtues and faults. Neither is very profitable by itself; each requires the assistance of the other. Statistical analyses check the accuracy of the assumptioms of the theorists, and the latter lend meaning to the empirical method. Unfortunately, however, in many cases there is no chance for mutual profit because the two approaches have no common ground. Until such contact has been established no branch of oceanography can quite be said to have come of age. In this respect physical oceanography, one of the youngest branches in actual years, is more mature than the much older study of marine biology. This is perhaps partly due to the complexities of the material. More important, however, is the fact that physical oceanography has aroused the interest of a number of men of considerable mathematical ability, while on the other hand marine biologists have been largely unaware of the growing field of bio-mathematics, or at least they have felt that the synthetic approach will be unprofitable until it is more firmly backed by experimental data.

However valid the latter objection may be, the present paper will attempt, in the limited field of plankton biology, to establish continuity between some purely descriptive studies that have been made and mathematical concepts based on what seem to be logical assumptions about plankton physiology. The need for such an attempt has

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become apparent during the course of several plankton surveys in which the data were analyzed statistically with the idea of correlating plankton populations and their rate of growth with various environmental factors such as solar radiation, temperature, dissolved nutrient salts, *etc.* In each survey a reasonably high degree of correlation was found, but the empirical nature of the relationships was often confusing. For example, temperature affects plankton in several different ways, and the relative importance of these effects varies from time to time and from place to place. The statistical relationship of temperature and plankton represents an average of these different effects. Therefore, it may happen in examining sets of data for particular areas and times that the temperature constant varies widely from set to set, and study of the values of their constants does not lead easily to a universally applicable theory.

Furthermore, there is no good reason for assuming that the variations of plankton with environment are always linear. To treat them as such may introduce an error. To evolve nonlinear relationships on a purely empirical basis is possible, but this generally requires a larger set of observations than is readily available.

These limitations of the statistical method will become apparent in the pages that follow. The only way to avoid them is by the opposite approach—that of developing the mathematical relationships on theoretical grounds and then testing them statistically by applying them to observed cases of growth in the natural environment. At present this can be done only tentatively, with over-simplification of theory and without the preciseness of mathematical treatment that might be desired. It is not expected that any marine biologist, including the writer, would fully believe all the arbitrary assumptions that will be introduced. However, the purpose of the paper is not to arrive at exact results but rather to describe promising techniques that warrant further study and development.

ACKNOWLEDGMENTS

My best thanks are due Dean F. Bumpus, who kindly provided me with the necessary zooplankton data, and Henry Stommel, who gave me valuable advice on some of the mathematical treatment.

STATISTICAL SECTION

Phytoplankton studies in the Georges Bank area of the western North Atlantic during the period from 1939 to 1941 have been described in a series of publications (Riley, 1941, 1942, 1943; Riley and Bumpus, 1946). In the first of these papers it was noted that part of the variations that occurred in the distribution of phytoplankton from one part of the bank to another and from one month to the next could be correlated with such factors as the depth of water, temperature and dissolved phosphate and nitrate. Since that time the study of the zooplankton collections has been completed and examination of the data has shown that grazing by zooplankton is important in controlling the size of the phytoplankton population. With the inclusion of the zooplankton material, it is now possible to develop a relatively complete statistical treatment of the ecological relationships of the Georges Bank plankton.

Observations. The original observations made during the 1939–1940 cruises were listed in the papers cited above. This material is briefly summarized in Table I in the form of means and standard deviations for each cruise. Correlations of phytoplankton with its various environmental factors have also been published. These have been used to develop multiple correlation equations by which the variations in horizontal distribution of plant pigments during each cruise are calculated according to the variations in environmental factors. Comparison of calculated values with the actual determinations for plant pigments shows an average error on the different cruises of 20–40%. In other words 60–80% of the variations in phytoplankton on Georges Bank can be accounted for on the basis of variations in depth, temperature, phosphate, nitrate and zooplankton. The multiple correlation equations for each cruise are as follows:

TABLE I. MEANS AND STANDARD DEVIATIONS OF GEORGES BANK PLANKTON AND ENVIRONMENTAL FACTORS

		Sept.	*Jan.*	*Mar.*	*Apr.*	*May*	*June*
Mean	*Depth of water in meters*	247	209	135	209	82	206
	Mean temperature, upper 30 m.	15.24	4.61	2.60	3.81	5.14	9.66
	Mg-atoms phosphate P per m², upper 30 m.	14.4	33.7	34.7	21.9	16.6	19.2
	Mg-atoms nitrate N per m², upper 30 m.	153	209	172	129	285	155
	Number of animals, thousands per m²	135	14	24	32	106	103
	Plant pigments, thousands of Harvey units per m²	560	118	828	2303	871	478
σ	*Depth*	540	371	163	530	357	458
	Temperature	2.14	0.71	0.33	0.37	0.39	2.58
	P	7.2	11.1	8.1	8.9	3.5	8.7
	N	108	209	68	129	79	155
	Zooplankton	126	13	18	38	77	85
	Plant pigments	195	67	781	827	522	233

Sept.: $PP = -.011D - 23.8t + 5.20P + .371N - .26Z + 829$

Jan.: $PP = .191D - 61.2t + 7.96P + .956N + .47Z - 115$

Mar.: $PP = -D - 770t - 23.18P - 6.98N - .62Z + 4989$

Apr.: $PP = .469D - 331t - 61.4P + .197N - 5.31Z + 4954$

May: $PP = .007D + 236t + 15.1P - 2.316N - 3.50Z + 437$

June $PP = -.066D - 48.1t - 15.5P + .070N - .55Z + 1300$

PP is thousands of Harvey units of plant pigments per m^2, D is depth of water, t is temperature, P is mg-atoms of phosphate P per m^2 in the upper 30 meters, N is mg-atoms of nitrate N, and Z is thousands of animals per m^2.

Discussion of the effect of environmental factors on the horizontal distribution of phytoplankton. The equations show, within the limits of error stated above, the amount of variation in the phytoplankton crop that is obtained by varying any one or all of the environmental factors. For example, at a particular station of the September cruise, if all the factors were found to have exactly the mean values as stated in Table I, then the plant pigments would be expected to have the mean value for September. If phosphate were increased one milligram-atom, it would increase the calculated value for plant pigments by the amount of the phosphate constant, or 5.2 thousands of units. If the phosphate varied a "normal" amount, as indicated by the limits of its standard deviation, the plant pigments would be changed ± 6.5%. Use of the standard deviation in this way is a convenient method of rating the importance of a given factor, and in Table II it is applied to all the variables in the equations. Although the standard deviation is a positive or negative variation around the mean, it serves a useful purpose to give the values in the table the same sign as the constant in the equation. The figures then represent the change in plant pigments produced by raising each factor from its mean to the upper limit of its standard deviation.

Table II shows that although one particular factor may be of outstanding significance, such as nitrate during the March cruise, phos-

TABLE II. PERCENTAGE CHANGE IN THE PHYTOPLANKTON CROP PRODUCED BY INCREASING THE VALUE OF EACH ENVIRONMENTAL FACTOR FROM ITS MEAN TO THE LIMIT OF ITS STANDARD DEVIATION

	Sept.	*Jan.*	*Mar.*	*Apr.*	*May*	*June*
Depth	−1	60	−20	11	0	− 1
Temperature	−9	−37	−31	− 5	10	−26
P	7	74	−23	−24	6	−28
N	7	41	−57	1	−21	1
Zooplankton	−6	5	− 1	− 9	−31	−10

phate in April, and zooplankton in May, there is no indication of complete control of the phytoplankton crop by a particular factor. It appears to be a highly complex relationship in which one factor after another gains momentary dominance. This table also shows that each variable has a vastly different significance at different times of the year, which is in accord with our present knowledge of phytoplankton ecology.

It has been shown (Riley, 1942) that the depth of water plays a significant role in the inception of the spring diatom flowering, and it is reasonable to find a strong negative relationship in March. This effect disappears later in the season when radiation becomes strong enough so that vertical turbulence is no longer able to prevent growth by dissipating the surface crop.

Temperature is generally supposed to have a negative effect on phytoplankton because increased respiration uses up part of the store of energy that would otherwise be used in the production of new plant material. The predominantly negative relationship shown in Table II is therefore expected. The positive relation in May is anomalous and not readily explainable.

The nutrient-phytoplankton relationship is one in which cause and effect are not clearly separable; although a large quantity of available nutrients is likely to stimulate growth, the growth-utilization process will reduce the quantity of nutrients so that the relationship becomes negative. The diversified results in Table II come from the complexities of this inter-relation. Probably the relationships are of three main types. First, in January, when the quantity of available nutrients was large and growth was slight because of low light intensity, the observed positive relationship is indicative of a slight stimulating effect by nutrients, which to a slight degree counteracted the inhibiting effect of insufficient light. Second, in spring, when radiation increased and growth became more abundant, negative relationships of the growth-utilization type were established. However, they did not become progressively stronger with the advance of the season, leading to complete exhaustion of nutrients; whether or not the observed partial exhaustion had an inhibiting effect on growth cannot be determined from these data. Third, a situation was established which was particularly apparent in September but which probably began early in the summer; in this situation the total quantity of plant pigments was fairly uniform all over the bank, but with certain localized areas of slightly higher crops accompanied by larger quantities of nutrients. These were sufficiently important to provide a direct relationship of a moderately low order between plankton and nutrients. They included some shallow water stations as well as four in deeper water (50 to 100 m.) on the northern and western edges of Georges Bank. In all cases the vertical distribution of temperature, as well as nutrients, was more nearly uniform than at near-by stations that had smaller crops. It is concluded, therefore, that the observed relationship was due to localized turbulence and upwelling of the nutrient-rich lower waters. Probably such conditions were of transient nature, for it seems likely that a degree of regeneration strong enough to maintain a positive nutrient-phytoplankton relationship for any length of time would lead to a much larger growth than was observed.

The phytoplankton-zooplankton relationship has been discussed in some detail in a previous paper (Riley, 1946) and need be only briefly summarized here. It was concluded that the predominantly negative relationship was due to grazing. The quantities of animals and plants were such as to indicate that the observed relationship could have been established in a very short time, possibly in a day or in a few days. A theory was postulated that tidal currents and turbulent motion of the Georges Bank waters tended continually to destroy the horizontal gradients in phytoplankton, but that the zooplankton, because of their habit of vertical migration, would be absent part of the time from the surface waters where mixing processes are strongest, and hence they would not be so readily dispersed. Therefore, they would tend constantly to reestablish the phytoplankton gradients by their grazing activity.

Effect of Environmental Factors on the Seasonal Cycle of Phytoplankton. It is apparent from the preceding discussion that the relationship of a particular environmental factor with the horizontal distribution of phytoplankton may differ from one month to another both in quantity and in kind. Nevertheless, there are seasonal trends in these factors which are related with plankton variations, as can be observed by inspection of the data in Table I. Thus the seasonal cycle of phytoplankton can be correlated with its environment with a fair degree of accuracy, even though such treatment makes no allowance for special effects that are operative only at particular times during the year.

A multiple correlation equation was developed from the cruise averages in Table I. It is

$$PP = -153t - 120P - 7.3N - 9.1Z + 6713.$$

The symbols are the same as in previous equations. The relation between the observed cruise averages and the values determined from the equation is shown in Fig. 14. The average error between observed and calculated values is 20%, which is slightly less than that obtained in the treatment of individual cruises. Probably the errors caused by

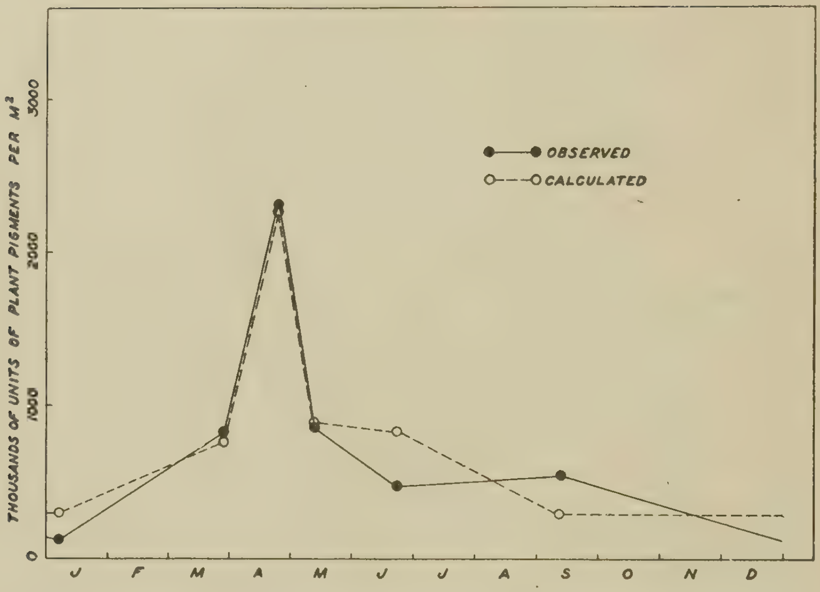

Figure 14. Comparison of the observed phytoplankton population with the calculated population as determined by a multiple correlation analysis of the relationship between phytoplankton and environmental factors.

ignoring certain special seasonal effects are more than counterbalanced by the reduction in analytical errors when averages are used for the calculation.

THEORETICAL SECTION

The rate of change of the phytoplankton population is determined by the difference in reaction rates between the process of accumulation of energy by the population and the processes of energy dissipation. It will be assumed that all the important reaction rates are included in the equation

$$\frac{dP}{dt} = P\,(P_h - R - G)\,, \tag{1}$$

in which the rate of change of the population P in respect to time is determined by the photosynthetic rate per unit of population (P_h), the rate of phytoplankton respiration (R), and the rate of grazing by zooplankton (G). Each of these rates is subject to environmental influences and therefore is continually changing with the seasons. In order to arrive at a practical solution of the equation it is necessary to examine each of its component parts in the light of present day plankton physiology.

A second major assumption will be that seasonal variations in environmental factors used in the analysis can be expressed by smooth curves drawn through the observed cruise averages. Since the latter are relatively incomplete, as far as the whole yearly cycle is concerned, there must be a certain amount of unavoidable error in the calculations.

Photosynthesis. Numerous investigators have reported that the photosynthetic rate in actively growing diatom cultures is proportional to light intensity within wide limits. The lower limit has not been determined accurately due to the insensitivity of the methods of measurement, but values of the right order of magnitude have been detected at depths where the light intensity was about 0.1–1.0% of the surface intensity in summer (Clarke, 1936). The upper limit of the proportionality is variable, depending on the species and the length of exposure; the optimum intensity for photosynthetic activity in particular situations has been reported to range from 1.8 g. cal. per cm^2 per hour (Jenkin, 1937) to 60 g. cal. (Curtis and Juday, 1937).

During the six cruises to Georges Bank between September 1939 and June 1940 two bottles of surface water were taken at each station and suspended in a tub of water on deck, one of them being covered with a bag of several thicknesses of dark cloth. After twenty-four hours' exposure the oxygen in the two bottles was measured and the difference in their oxygen content was used as a rough estimate of the photosynthetic activity of the surface plankton. The inset in Fig. 15 shows the average photosynthetic rate[2] obtained on each cruise plotted against the average incident solar radiation in the area at that time of year. Radiation values are obtained from data published by Kimball (1928) and reproduced in Sverdrup, Johnson and Fleming (1942: 103). The plotted points for the January, March, April and May cruises approximate a linear relationship in which the photosynthetic rate equals 2.5 times the incident radiation in g. cal. per cm^2 per minute. The June and September rates are lower, but it will be shown later that this can be explained as a result of nutrient depletion.

With these facts at hand the mean photosynthetic rate of the population will be estimated according to the following assumptions:

1. When nutrient depletion does not limit photosynthesis,

$$P_h = pI \tag{2}$$

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[2] The photosynthetic rate is expressed as grams of carbon produced per day per gram of carbon in the surface phytoplankton crop, using the formula photosynthetic rate = .375 × oxygen production in g/m^3/day ÷ 17 × 10^{-6} Harvey units of plant pigments/m^3. The conversion factor is based on analyses described in a previous paper on the plankton of Georges Bank (Riley, 1941).

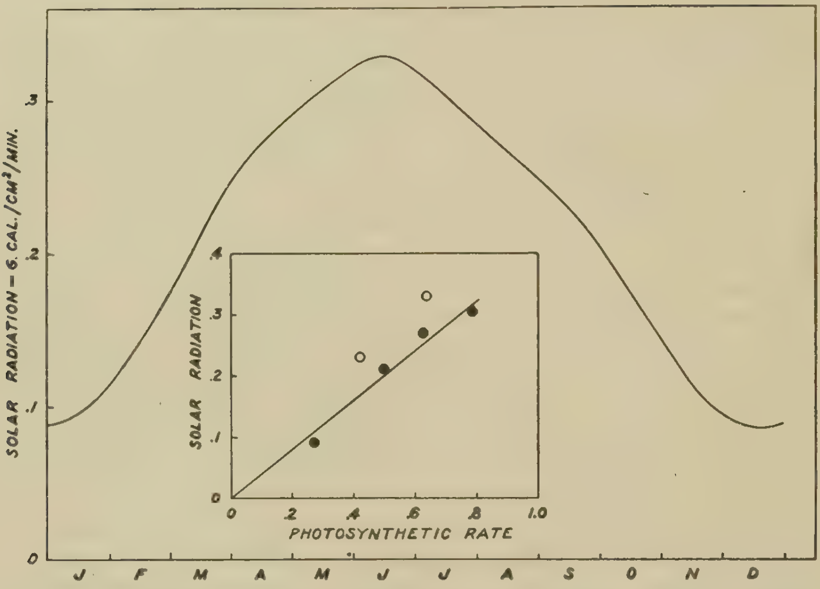

Figure 15. Seasonal variations in average incident solar radiation in the Georges Bank area. Inset shows average observed surface photosynthetic rate plotted against incident radiation. Dots are averages for January, March, April and May; circles are June and September.

in which P_h is the photosynthetic rate, I is radiation in g. cal./cm²/minute at the depth of the photosynthesizing plankton, and p, the photosynthetic constant, is 2.5.

2. The intensity at the surface, I_o, may be determined for any time in the year from the curve in Fig. 15, which is based on Kimball's data, cited above.

3. The intensity at any other depth z is determined from the formula

$$I_z = I_0 e^{-kz}$$

and therefore

$$P_{hz} = pI_0 e^{-kz}. \tag{3}$$

In these formulas the extinction coefficient k is defined as 1.7 divided by the depth of the Secchi disc reading, a rough conversion factor suggested by Poole and Atkins (1929). Secchi disc determinations for the Georges Bank area are shown in Fig. 16.

4. According to equation (3) the photosynthetic rate approaches zero as the depth approaches infinity. But the depth at which a measurable and significant amount of photosynthesis occurs is limited, and so is the depth at which viable phytoplankton can be found.

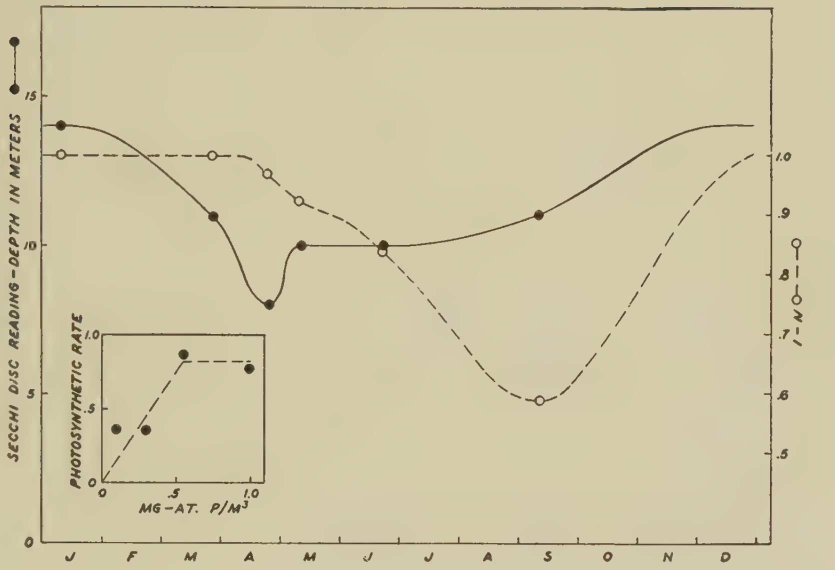

Figure 16. Solid curve is transparency as determined by Secchi disc readings. Dotted line is the estimated reduction in photosynthetic rate caused by nutrient depletion. Inset shows averages of photosynthetic rate plotted against phosphate concentration during June and September.

Therefore, it is convenient to set an arbitrary limit to the depth of the euphotic zone. This depth will be called z_1 and will be defined as the depth at which the light intensity has a value of 0.0015 g. cal./cm²/minute. This approximates the intensity at the maximum depth of photosynthesis as reported by Clarke (1936). Calculated values for z_1 are shown in Fig. 17.

5. To find the mean photosynthetic rate in the euphotic zone, equation (3) is integrated from the surface to z_1, and divided by z_1:

$$\overline{P_h} = \frac{pI_\circ \int_0^{z_1} e^{-kz}\,dz}{z_1} = \frac{\left.\frac{pI_\circ}{-k}\, e^{-kz}\right|_0^{z}}{z_1}$$

$$\underset{0 \longrightarrow z_1}{\overline{P_h}} = \frac{pI_\circ}{kz_1}(1 - e^{-kz_1})\,. \tag{2}$$

6. It was postulated that the proportionality between photosynthesis and radiation holds only when nutrients are abundant. The fact noted previously that the ratio between the photosynthetic rate and light intensity was reduced in June and September led to an in-

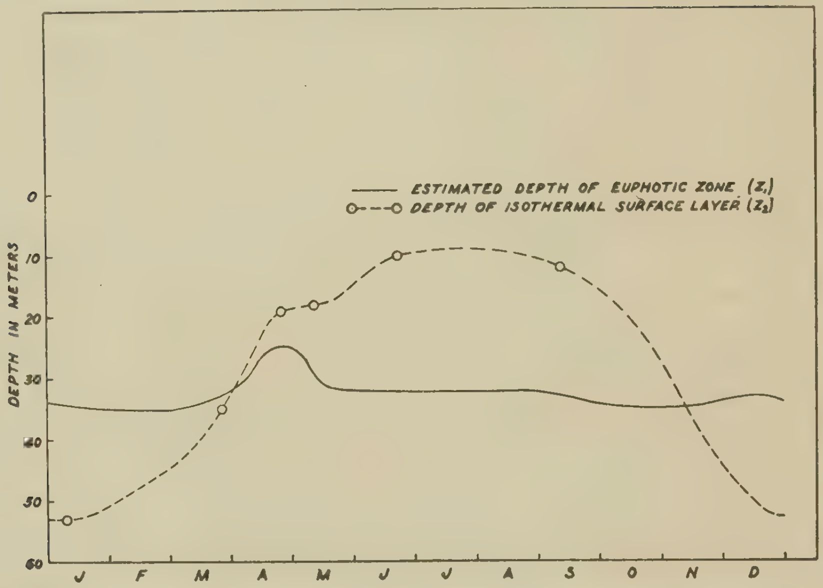

Figure 17. Estimated depth of the layer in which a measurable amount of photosynthesis occurs (z_1), and the depth of the virtually isothermal surface layer (z_2).

vestigation of nutrients as a possible cause. Large individual variations were found, and the correlation between photosynthetic rate and phosphate concentration was poor; nevertheless, when the rates were averaged for different ranges of phosphate concentration, there was a pronounced reduction in the average rate when the phosphate fell below about 0.5 to 0.6 mg-atom of P per m^3 (Fig. 16, inset). Ketchum (1939) reported a decrease in the growth rate of experimental cultures of *Nitschia closterium* when the phosphate concentration was less than 50 gamma of PO_4 per liter (0.55 mg-atom per m^3). Therefore it seems reasonable to assume that the mean photosynthetic rate as determined in equation (4) should be multiplied by a factor $(1 - N)$, in which N is the reduction in rate due to nutrient depletion. According to the facts above,

$$N = \frac{0.55 - mg\text{-}at.\ P/m^3}{0.55} \qquad \text{when } P \leqq 0.55.$$

Mean values for $(1 - N)$ are shown in Fig. 16.

7. Several investigators have pointed out the importance of vertical turbulence in reducing phytoplankton crops by carrying the breeding stock below the euphotic zone. That this is an important phenomenon on Georges Bank has been demonstrated (Riley, 1942). If turbulence

is such that each phytoplankton cell spends only a certain proportion of its time in the euphotic zone, then the mean photosynthetic rate of the population as a whole will be reduced. Therefore equation (4) should be multiplied by still another factor $(1 - V)$, in which V is the reduction in rate produced by vertical water movements. It is impossible to define V in any simple way that will be entirely satisfactory, but as an approximation,

$$(1 - V) = \frac{z_1}{z_2} \text{ when } z_1 \leqq z_2,$$

in which z_1 is the depth of the euphotic zone as previously defined and z_2 the depth of the mixed layer, which is arbitrarily defined as the maximum depth at which the density is no more than 0.02 of a σ_t unit greater than the surface value. Fig. 17 shows the estimated values for z_1 and z_2 for Georges Bank.

The final equation for the mean photosynthetic rate is now

$$P_h = \frac{pI_0}{kz_1}(1 - e^{-kz_1})\,(1 - N)\,(1 - V). \tag{5}$$

The application of the equation to the Georges Bank data is shown in Fig. 18. The upper curve shows the primary calculation of the photo-

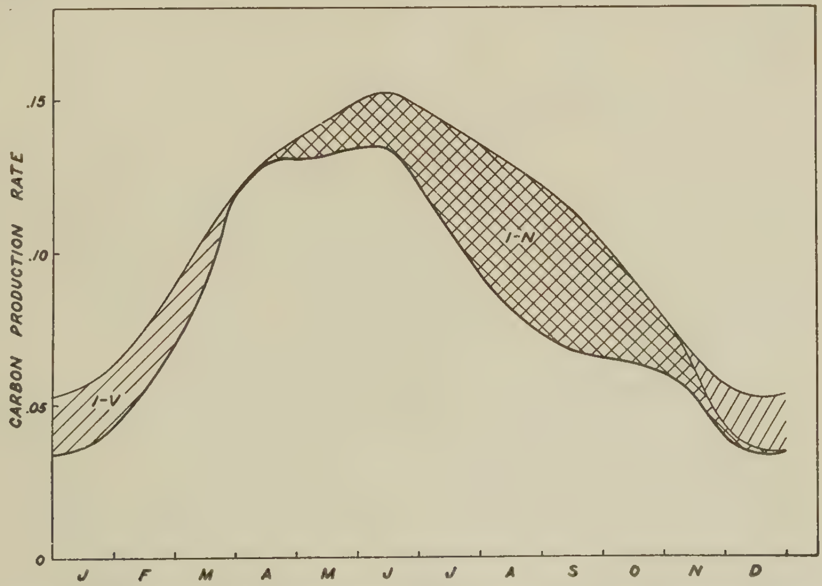

Figure 18. Estimated mean photosynthetic rate. Upper curve is the maximum possible rate as determined by incident radiation and transparency. Lower curve is the estimate obtained by introducing correction factors for the effects of vertical turbulence and nutrient depletion.

synthetic rate based on light intensity. The reduction obtained by introducing $(1 - N)$ and $(1 - V)$ is indicated by hatched areas. The heavy lower curve is the final estimate of the mean photosynthetic rate.

Phytoplankton respiration. The few available measurements of the respiration of pure diatom cultures have not yielded precise results. Observed rates have varied from one species to another as well as during different stages of growth of the same culture. The recorded values differ by a factor of 10 to 20, and there are not enough of them to draw a good average.

No direct measurements have been made of the respiration of a natural phytoplankton population, since the measured oxygen consumption also includes zooplankton and bacterial respiration. Statistical estimates have been made by the writer on the basis of the observed correlation between phytoplankton and total oxygen consumption. The best of these, judging by quantity and homogeneity of data, was obtained in Long Island Sound (Riley, 1941a). It was estimated that in winter (average temperature 2.05° C.) the respiration rate was 0.024 ± 0.012 mg. of carbon consumed per day per mg. of phytoplankton carbon. Calculations based on summer observations suggested that the respiration increased with higher temperatures (0.110 ± 0.007 at 17.87° C.), the rate being approximately doubled by a 10° increase in temperature.

On the basis of these rather scanty data it will be assumed that:

1. The temperature effect can be stated as

$$R_T = R_o e^{rT} \qquad (6)$$

in which R_T is the respiratory rate at any temperature T, R_o is the rate at 0° C. and r is a constant expressing the rate of change of the respiratory rate with temperature. The value of r is 0.069 when the rate is doubled by a 10° increase in temperature. The seasonal cycle of Georges Bank surface temperatures used in computing respiratory rates is shown in Fig. 19.

2. The value chosen for R_o will be 0.0175. This is the mean of the two estimates derived from the Long Island Sound data mentioned above, in which the calculated values of R_o for winter and for summer are respectively 0.020 and 0.015.

Grazing. The greater part of the zooplankton population consists of filter-feeding organisms which tend to strain a relatively constant volume of water in a given time irrespective of the quantity of food material in it. Therefore a fixed proportion of the phytoplankton population will be consumed in successive units of time. This is stated as

$$G = gZ\,, \qquad (7)$$

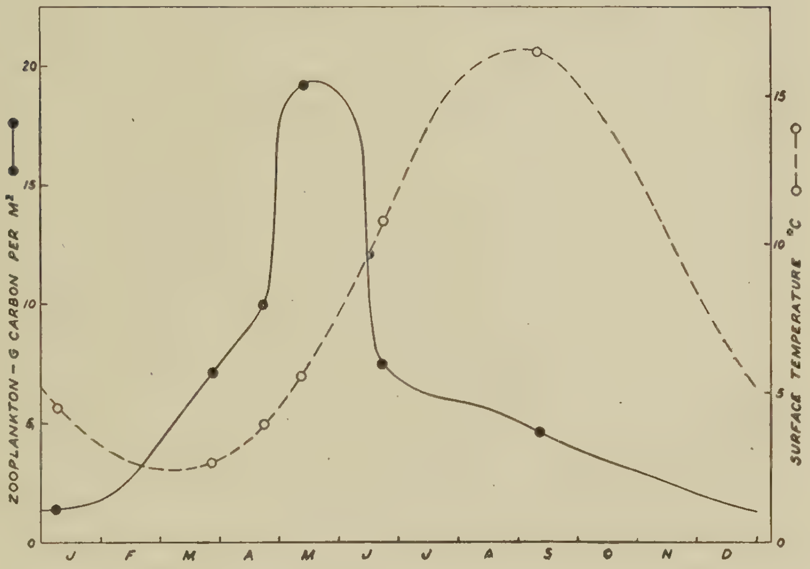

Figure 19. Solid line is the seasonal cycle of zooplankton. Measurements of zooplankton volume by the displacement method are treated by a conversion factor (wt. in g. = 12.5% × vol. in cc.) to derive a rough estimate of the carbon content. Dotted line is the mean surface temperature.

in which G is the rate of grazing, g is the rate of reduction of phytoplankton by a unit quantity of animals and Z is the quantity of zooplankton in grams of carbon per m².

There is some question as to whether g is nearly constant over long periods of time or undergoes a marked seasonal change. On the one hand there are the experiments of Marshall, Nicholls and Orr (1935) which showed that the respiratory rate of *Calanus finmarchicus* increases with increasing temperature, implying a greater food requirement at higher temperatures and possibly an increased filtering rate. On the other hand, feeding experiments by Fuller (1937) showed variations of a more complex nature. The grazing rate of *Calanus finmarchicus* was greater at 8° C. than at 3° or 13° C., and animals captured in the late summer, when the natural breeding stock was declining, had lower feeding rates than those studied earlier in the summer. Thus a factor that can be called "depressed physiological state" for want of a more precise term appears to counterbalance the expected effect of high temperature late in the summer. It is clear that the whole process of zooplankton feeding requires much more thorough study. However, lacking the necessary information to describe the process accurately, it is believed that it can best be approximated by the simple form of equation (7).

The value of g must be of an order of magnitude which will at least satisfy the minimum respiratory requirements of the zooplankton population at times when the latter is stable. According to Marshall, Nicholls and Orr (1935), the daily food requirement of *Calanus* in winter (5° C.) lies between 1.3 and 3.6% of the carbon content of the animals. This estimate applied to the January plankton on Georges Bank yields a grazing constant of 0.0091 to 0.0252. In summer (15° C.), these authors suggest a food requirement of 1.7–7.6%, for which the corresponding values of g are 0.0084 to 0.0374 in September on Georges Bank. The latter estimates are perhaps too high, since the zooplankton was decreasing at a rate of 0.5% per day and therefore probably was not getting enough food to satisfy the minimum respiratory requirements. If it is assumed that the food intake equaled the food requirement minus the rate of population decrease, then the food intake was 1.2–7.1% of the animals' carbon content per day, and the corresponding values for g are 0.0059 and 0.0350.

Within these wide limits it is difficult to choose a correct value for the grazing constant, and again the need for more experimental work is apparent. On a purely empirical basis, a good fit for the data is obtained by using the average of the minimum values of g for the September and January cruises, namely 0.0075. This factor, multiplied by the quantity of zooplankton, shown in Fig. 19, estimates the Georges Bank grazing rate.

Conclusions. The original equation

$$\frac{dP}{dt} = P\,(P_h - R - G)$$

can now be expanded by substituting the right hand terms of equations (5), (6) and (7):

$$\frac{dP}{dt} = P\left[\frac{pI_\circ}{kz_1}\,(1 - e^{-kz_1})\,(1 - N)\,(1 - V) - R_\circ e^{rT} - gZ\right]. \quad (8)$$

The rate of change of the population is dependent on six ecological variables: the incident solar radiation, transparency of the water, the quantity of phosphate, the depth of the mixed layer, the surface temperature and the quantity of zooplankton. The results of the application of equation (8) to the Georges Bank data are shown graphically in Fig. 20. The curve at the top is the photosynthetic rate previously illustrated (Fig. 18). The second curve is the photosynthetic rate minus the respiratory rate of the phytoplankton, or in other words the

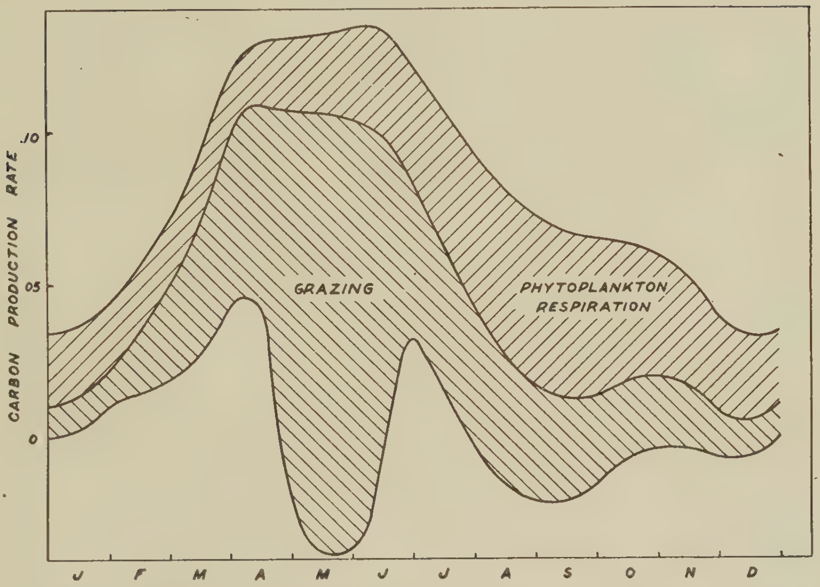

Figure 20. Estimated rates of production and consumption of carbon. Curve at top is the photosynthetic rate. By subtracting the respiratory rate the second curve is obtained, which is the phytoplankton production rate. From this is subtracted the zooplankton grazing rate, yielding the curve at the bottom, which is the estimated rate of change of the phytoplankton.

phytoplankton production rate. By subtracting the grazing rate from the production rate, the rate of change of the population is obtained. This is the bottom curve of Fig. 20. Numerical values used in drawing these curves are shown in the appendix.

Equation (8) cannot be integrated readily, but an approximation is obtained by integrating over successive short intervals of time and assuming for each variable a constant, average value during that time. Thus the change in population in the time interval 0 to t is determined by

$$lnP_t - lnP_o = \overline{P_h} - \overline{R} - \overline{G}\,.$$

Therefore, by a series of integrations the quantity $lnP_t - lnP_o$ can be approximated for the whole seasonal cycle. This quantity indicates the relative size of the population from one part of the cycle to another. To convert to absolute terms requires evaluation of the integration constant P_o (the size of the population at the minimum point in the cycle), which is readily obtained if the quantity of plankton (P_t) is measured at one or more times during the year. In the present case, in which six cruise averages are available, P_o was statistically determined so as to give the best fit for the data. The results are shown in Fig. 21, in which the theoretical population cycle is shown by a smooth curve, and the observed cruise averages are indicated by dots. The average error is 27%.

It is now apparent that a few simple and commonly measured environmental factors can be used with a fair degree of accuracy to evaluate the quantitative aspects of the seasonal cycle of phytoplankton. Furthermore, this can be done in two different ways: first by statistical comparison of the simultaneous variations of phytoplankton and environmental characteristics in a particular locality; second, by theoretical evaluation of the way in which changes in the environment might affect growth as evidenced by the results of various physiological experiments. Each of these methods has something to contribute to plankton biology. The statistical method is useful in determining whether a particular factor is significant; the theoretical method carries on from there, discriminating between cause and effect and helping to establish certain quantitative relationships that are not likely to be derived empirically.

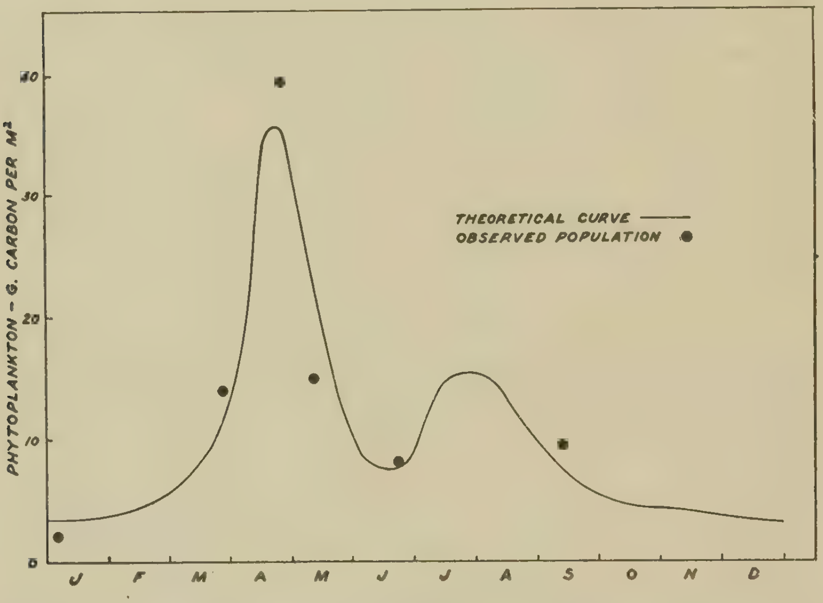

Figure 21. Curve shows the calculated seasonal cycle of phytoplankton, determined by approximate integration of the equation for the rate of change of the population. For comparison the observed quantities of phytoplankton are shown as dots.

While these methods are obviously crude at the present time and need to be developed further, both by examination of other areas and by better experimental evaluation of constants, it does not seem too much to hope that they will eventually solve some of the problems of seasonal and regional variations that puzzle marine biologists today.

SUMMARY

1. Variations in the phytoplankton population of the Georges Bank area are correlated with various environmental factors. Equations are developed statistically by which the size of the population can be calculated on the basis of such factors as temperature, depth of water, and the quantities of nitrate, phosphate and zooplankton. Calculated horizontal variations in the plankton crop at various times in the year differ from observed values by about 20–40%. Calculations of the seasonal variation of the average crop in the area are accurate within about 20%.

2. The seasonal cycle of phytoplankton is also evaluated from a more theoretical standpoint. It is postulated that the rate of change of the phytoplankton population is equal to the photosynthetic rate minus the phytoplankton respiratory rate minus the grazing rate of the zooplankton. Factors affecting these rates are discussed, and the ones that are considered particularly important are solar radiation, temperature, transparency of the water, the depth of the isothermal surface layer, phosphate, and zooplankton. The observed variations of these factors are combined with appropriate constants derived from experimental data to develop an equation that expresses the seasonal rate of change of the phytoplankton population. Approximate integration of the equation yields a population curve of the same order of accuracy as the statistical estimate.

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APPENDIX

Numerical Value of Quantities Used in the Calculation of the Seasonal Rate of Change of the Georges Bank Phytoplankton Population as Developed in the Theoretical Section of This Paper

Date	I_o	k	z_1	$1-N$	z_2	$1-V$	Ph	T	R_T	Z	G	dP/dt	lnP_t-lnP_o	lnP_t	P_t
1/1	.088	.121	34	1.00	53	.64	.034	5.2	.024	1.3	.010	.000	.000	1.217	3.4
1/15	.094	.121	34	1.00	53	.64	.036	4.1	.023	1.4	.011	.002	.030	1.247	3.5
2/1	.112	.124	35	1.00	51	.69	.044	3.2	.021	1.7	.013	.010	.180	1.397	4.0
2/15	.138	.128	35	1.00	48	.73	.055	2.7	.021	2.6	.020	.014	.390	1.607	5.0
3/1	.174	.136	35	1.00	45	.78	.071	2.4	.021	4.2	.031	.019	.675	1.897	6.7
3/15	.212	.145	34	1.00	40	.85	.091	2.5	.021	5.8	.043	.027	1.080	2.297	10.0
4/1	.247	.159	32	1.00	32	1.00	.120	2.7	.021	7.5	.056	.043	1.725	2.942	19.1
4/15	.272	.200	26	1.00	23	1.00	.130	3.4	.021	8.9	.067	.042	2.355	3.572	35.5
5/1	.290	.205	25	.95	19	1.00	.131	4.5	.024	17.2	.129	−.022	2.025	3.242	25.7
5/15	.306	.170	31	.92	18	1.00	.132	5.9	.026	19.3	.145	−.039	1.440	2.657	14.2
6/1	.321	.170	32	.90	15	1.00	.134	7.6	.030	18.8	.141	−.037	.885	2.102	8.2
6/15	.329	.170	32	.88	11	1.00	.134	9.7	.035	14.0	.105	−.006	.795	2.012	7.5
7/1	.319	.170	32	.82	10	1.00	.122	11.8	.038	6.9	.052	.032	1.275	2.492	12.1
7/15	.302	.170	31	.76	9	1.00	.108	13.9	.045	6.2	.047	.016	1.515	2.732	15.4
8/1	.284	.165	32	.69	9	1.00	.093	15.5	.051	6.0	.045	−.003	1.470	2.687	14.8
8/15	.267	.162	32	.63	10	1.00	.081	16.3	.054	5.7	.043	−.016	1.230	2.447	11.5
9/1	.250	.159	32	.60	11	1.00	.073	16.6	.056	5.1	.038	−.021	.915	2.132	8.4
9/15	.230	.154	33	.59	13	1.00	.067	16.4	.054	4.5	.034	−.021	.600	1.817	6.1
10/1	204	.145	34	.63	16	1.00	.065	15.5	.051	3.9	.029	−.015	.375	1.592	4.9
10/15	.174	.138	34	.69	20	1.00	.063	14.2	.045	3.3	.025	−.007	.270	1.487	4.4
11/1	.144	.131	35	.77	27	1.00	.060	12.4	.040	3.2	.024	−.004	.210	1.427	4.2
11/15	.115	.126	35	.85	37	.95	.053	10.5	.037	2.6	.020	−.004	.150	1.367	3.9
12/1	.094	.121	34	.92	45	.76	.039	8.5	.031	2.0	.015	−.007	.045	1.262	3.5
12/15	.086	.121	33	.97	50	.66	.033	6.7	.028	1.6	.012	−.007	−.060	1.157	3.2

I_o = incident solar radiation in g. cal./cm^2 1 /cm^2/minute
k = extinction coefficient = 1.7/Secchi disc reading in meters
z_1 = depth of euphotic zone in meters, defined as depth where the light intensity is .0015 g. cal.
$1 - N$ = correction factor for nutrient depletion = mg-at. phosphate P/0.55 when $P \leqq 0.55$.
z_2 = depth of mixed layer = maximum depth at which $\sigma_{tz} - \sigma_{t_o} \leqq 0.02$.
$1 - V$ = correction factor for vertical turbulence = z_1/z_2 when $z_1 \leqq z_2$.
Ph = estimated mean photosynthetic rate according to equation (5) in text.
T = mean surface temperature.
R_T = estimated phytoplankton respiration according to equation (6).
Z = g. of zooplankton carbon/m^2, estimated on the assumption that the weight of carbon in grams = 12.5% of the volume (by displacement) in cubic centimeters.
G = grazing rate = $0.0075Z$
dP/dt = rate of change of the phytoplankton population = $Ph - R - G$.
$lnP_t - lnP_o$ = the summation of 15 × dP/dt (since the rate determinations are at approximately 15-day intervals)
lnP_t = $lnP_t - lnP_o + 1.217$. The latter is a value for P_o determined statistically as the best fit for the observed population data.
P_t = estimated population in g. of phytoplankton carbon/m^2 (considered equivalent to 17 × Harvey units of plant pigments $\times 10^{-6}/m^2$).

Contribution No. 354

The team was provided with a photographically equipped aircraft (B-25) and with surface craft (DUKWS and LCCS). The increased liaison facilities afforded by this equipment made for better cooperation with established field reconnaissance organizations.

A high degree of cooperation was maintained within the team. All personnel, regardless of status, were given training in the basic principles of oceanography, and were cognizant of the methods and techniques employed. Key personnel who had access to operational plans had the responsibility of processing all final data and of estimating its significance to landing craft and other assault instruments.

Services of a tactical military oceanographic unit

The following breakdown of services was provided by a military oceanographic team to an operation in the combat zone; (a) the planning and training phase, (b) the assault phase, and (c) the buildup and supply phase.

The planning and training phase--This phase involves five services, as follows:

1. Special beach and hydrographic charts for specific locations were generally prepared by adding information to existing hydrographic charts and redrafting to suitable scales. The additional information was partially taken from publications, but a certain amount was always obtained by local reconnaissance. As the latter was usually restricted to the air, methods were developed to estimate beach gradients, underwater depths, and other hydrographic factors from aerial photographs. The charts show the following information for the target beaches: physical state of the beach, beach gradients, beach composition with reference to trafficability and road-building materials, suitable landing-craft areas, beach exits, and landing-craft hazards.

2. Twelve and 24-hour forecasts of state of the sea and surf in the vicinity of target beaches. This represents one of the major wartime developments in military oceanography. The initial research was instigated by the Military Oceanographic Unit during the planning stage of the Northwest African invasion (operation TORCH). The method finally devised was chiefly a result of the work of the Director of the Scripps Institution of Oceanography, called in at the request of the Military Oceanographic Unit. Although the earlier method did not play too prominent a role in the landings, its possibilities were realized, and stimulation of research on surface conditions of the ocean eventually led to the development of the present reasonably accurate method of forecasting the state of the sea and surf for any part of the World's oceans.

3. Preparation of a Daily Hydrographic Bulletin giving, in tabular form, a 24-hour hour-by-hour forecast of the probable hydrographic conditions affecting assault craft and other invasion equipment along target coasts. For its preparation, results of measurements on beach gradients, underwater depths, and the operational drafts of specified landing craft were combined with tidal predictions and state of the sea forecasts and other relevant hydrographic data. The final result was a reasonably complete condensation of hydrographic conditions as they might be expected to affect invasion equipment on the target. Hourly data were given for the following; height of surf, period of surf, depth of water at breaking surf, number of lines of surf, distance from breaking surf to first available cover on beach, relationship of grounding of landing craft to breaking surf, height and period of waves between line of departure and beaches, height and period of waves at locations of transfer of personnel from transport to landing craft, direction and velocity of surface currents, estimated drift of landing craft (velocity and direction) between line of departure and beach, degree of solar illumination, air temperature, distance from grounding of landing craft to nearest available cover, and depth of water over enemy defenses.

4. Preparation of tidal illumination diagrams. These were originally devised by the Oceanographic Unit for the early amphibious operations. They showed diagrammatic relationships between times of high and low tide and the degree of solar illumination. The three types of twilight are indicated so as to bring out gradation of light from sundown through darkness, as well as from darkness through sunrise.

5. Consultants for all other military oceanographic matters.

The assault phase--The oceanographic team lands with the assault troops to be available for consultation and liaison purposes and to make essential surveys and observations. Preparation and dissemination of the Daily Hydrographic Bulletin was continued.

The buildup and supply phase--This phase involved the following five services: (1) Surveys of beaches to determine most suitable locations for unloading different classes of supplies from landing craft; (2) continuation of forecasts of sea and swell, specifically interpreted in terms of the supply program; (3) special surveys to determine locations for removal of sand, gravel, and other road-building materials from the beach, with special attention to exit points; (4) preparation of tables showing hourly depths of water over critical sills; and (5) special hydrographic surveys for forecasting state of the sea.

Military oceanography in the European Theater of Operations

In the spring of 1944, the Chief of the Military Oceanographic Unit of the Army Air Forces was ordered to the European Theater of Operations as Consulting Oceanographer. At that time, special charts of the Normandy target beaches were in preparation, and a sea-swell forecasting service had been set up in the Theater. However, early discussions with staff officers of Theater Headquarters and the First United States Army indicated that the separate hydrographic services in the Theater should be coordinated, and that a daily hydrographic bulletin and tidal illumination diagrams should be prepared for the Normandy targets. To accomplish this a small group of personnel was hastily organized in the office of the Chief Engineer of the European Theater early in May, 1944.

For the assault phase, the Theater Oceanographer was attached to the forward headquarters of an engineer group, and plans were made to provide him with limited personnel in France after the initial beach landings. Preparation of the Daily Hydrographic Bulletin just previous to and during the initial assault stages was carried out by two specially trained meteorological officers while afloat. The assembly of the oceanographic personnel on Omaha Beach in the early stages of the assault initiated the first oceanographic combat team in history.

In the early days of the Normandy operation, the Military Oceanographic Unit performed a variety of duties in connection with the organization of the beaches and their logistical development. In addition to preparing on-the-spot forecasts of state of the sea and surf for the early critical supply and buildup operations, survey parties were organized on both Omaha and Utah beaches to obtain hydrographic data (beach topography, tides, currents, surf, etc.) for comparison with prelanding information and for the use of the beach organizations. Other surveys were made to estimate the effects of removal of beach shingle on the roadways and exit points. Studies were undertaken to determine the effects of wave heights on cargo operations. The inverse relationships between wave heights and tonnage unloaded were worked out for the DUKW operations between shore and the cargo ships moored in exposed anchorages.

In the latter part of August, 1944, oceanographic headquarters were set up in Paris. An Oceanographic Section was then formally established in the Office of the Chief Engineer, and personnel increase of American military and French civilians was sufficient to take care of the work. Two French Naval officers were attached for liaison with the French Hydrographic Office. Military personnel of the Oceanographic Section formed the nucleus for the 6812 Engineer Technical Intelligence Team--Oceanography and Beaches, activated in the European Theater of Operations in December 1945. Because of the large number of practical tidal problems with which the Oceanographic Section became involved, the United States Coast and Geodetic Survey loaned the Chief of its Tidal Division for four months' duty. The work of this officer was invaluable in formulating the practical tidal problems with which port operations were confronted and in clearing the confusion which had resulted from the various tide tables in circulation.

Near the end of the winter of 1944-45, key personnel of the Oceanographic Section were ordered to the United States to constitute the nucleus of a military oceanographic organization for the Pacific Theater.

Military oceanography in the Pacific Theater

The problems posed by the request of the United States Army Headquarters in the Pacific Ocean areas for a Military Oceanographic Unit to be organized and trained for duty in that Theater chiefly concerned the procuring of suitably trained personnel. At that time (1945) technically trained personnel were established, and there was known to be a serious shortage of the type required for this unit. It was with this in view, as well as to obtain information on Pacific Theater requirements, that the Commanding Officer of the European Theater Team was ordered to the Pacific shortly after returning from Paris. After conference with the staff of Pacific Headquarters he returned to the continental United States with orders to procure, organize, and train a Military Oceanographic Unit from material available.

The strength of the new Military Oceanographic Unit was fixed at 61 officers and men. In addition to the Commanding Officer and Adjutant, its personnel were divided as follows: (a) 17 oceanographers, meteorologists, and geologists; (b) 19 aerial photographers, phototopographers, and photo interpreters; (c) 15 draftsmen, computers, and technicians; and (d) eight clerks and stenographers.

One of the officer meteorologists was a rated pilot who flew the Unit's photo-equipped B-25 aircraft. Other personnel were selected on the basis of their technical training, as well as previous backgrounds of marine engineering and seamanship. Their additional duties included operating the Unit's surface craft.

Screening of officers and men for suitable qualifications began in April, 1945, and in May, 1945 the complete Unit was assembled at Orlando, Florida, for one month of intensive training in aerial photographic methods and physical oceanography. Training in physical oceanography consisted of a series of lectures by the leading physical oceanographers in the country, including the Directors of the two Oceanographic Institutions.

After arrival in the Pacific Theater the Military Oceanographic Unit was attached to the highest headquarters of the Olympic assault operation. Key personnel were placed in contact with operational staffs of the various task forces. At the War's end the Unit was in the process of assembling and analyzing oceanographic and beach information pertinent to the accepted assault plans. New information was acquired from special studies of aerial photographs obtained from Theater Intelligence agencies. If the Olympic operation had been carried out, part of the Unit would have landed on the beaches with the assault troops so as to undertake special hydrographic and beach surveys for the logistical development of the beach areas and to check pre-landing information. The remainder of the Unit was to remain afloat and prepare state of the sea forecasts and other pertinent information for use in the early buildup stages. The project was similar to the oceanographic plan of the Normandy operation. It was more complete because of increased personnel and the background of experience gained from that operation.

Although active warfare in the Pacific ended before the Military Oceanographic Unit got into combat, a part of it participated in a practice maneuver with a combat infantry division in training for the Japanese assault. The following brief description of the oceanographic service provided for this maneuver may help clarify the picture of an organized oceanographic service in actual combat.

The maneuver took place on a Pacific island previous to V-J day. The plan called for a regimental combat team to assault a specified beach with two battalions abreast. After securing of the initial beachheads, it was to hold and defend until passed through by the reserve regimental team. The Oceanographic Service was designed to provide pertinent pre-landing data for use in the maneuver, and trained personnel in the exercise pattern, whose duties were to keep the Commander and staff informed of impending sea conditions between the transport areas and the beaches, and of surf conditions on the target.

The distribution of personnel was that one oceanographer remained on the command ship; two state of the sea forecasters were stationed at a Weather Central, and two state of the sea observers landed with an early assault wave. During the principal day of the maneuver, a member of the Oceanographic Unit photographed the exercise from the air.

The duties of the individuals were as follows: Oceanographer, on board the command ship, prepared a Daily Hydrographic Bulletin showing the expected hour-by-hour states of the sea, tides, and currents and their effects on the types of landing craft in use. He also informed the Command Staff of impending changes in sea conditions affecting the operation; two state of the sea observers, landed with an early assault wave to observe heights, periods, and wave lengths of sea and surf on the target beaches, and to note the effects of sea conditions on landing craft. Their observations were transmitted by the shore party message center to the command ship, from where they were relayed to the Weather Central for use of the state of the sea forecasters; two state of the sea forecasters, on duty at a distant permanent Weather Central prepared 24-hour state of the sea forecasts every 12 hours for transmission to the oceanographer on board the command ship.

The forecasts were made daily and radioed to the Infantry Division Message Center at 12^h00^m and 24^h00^m. The noon forecasts covered the 24-hour period from 18^h00^m of that day until 18^h00^m the following day. The night forecasts covered the 24-hour period from 06^h00^m to 06^h00^m the following day. Information on the state of the sea was available continuously throughout the entire period of the maneuver. Each forecast was a 24-hour prognosis of state of the sea and surf for the areas concerned.

After cessation of hostilities the entire Oceanographic Unit was reassembled at a rear headquarters in the Pacific and a three month oceanographic research program undertaken. This program was planned to take stock of the characteristics and limitations of certain selected aerial methods for measuring underwater depths and of methods for forecasting sea swell and sea surf. Both of these had obtained vital operational importance during the recent War, and military oceanographers had encountered various perplexing problems during operational use. The methods had been developed under conditions of war expediency as a means of obtaining hydrographic data, and the normal peacetime scientific procedures were altered in the interests of expediency. Often practical rule of thumb methods were devised at the sacrifice of adequate recording and experimentation. During the War the results justified the means.

Three months were spent obtaining pertinent observations and reducing them in an elementary fashion. It was originally planned that a comprehensive analysis of the results would be undertaken when facilities were available for the necessary scientific coordination. To date, one study dealing with an appraisal of the Sonne Stereo camera for underwater depth determination has been published [BEACH INTELLIGENCE UNIT, 1946]. It is desirable that a thorough investigation be made of technical methods developed during the War and recorded for future scientific and military study, as well as for an appraisal of their application to peacetime problems.

The future of military oceanography

The peacetime development of scientific military methods and counter measures for future wars will undoubtedly decide the fate of this Nation. The power of modern science applied to instruments of warfare over previous standardized strategical and tactical doctrines has been aptly demonstrated. Little imagination is required to visualize the necessity that this Nation maintain a superior scientific military research program.

Oceanography embraces all studies on the oceans of the world. Military oceanography is the application of this information to military strategy and tactics and appears to be a sphere of investigation inseparable from future military developments. The archaic conception that the science of oceanography falls exclusively within the province of naval operations is admission of lack of vision and imagination. Thus, the greatest operations of the recent War were the so-called "combined operations" in which Army, Navy, and Air Forces operated under a single unified command. Because these operations were assaults on enemy coastal areas, initial problems concerned the military oceanography of the target, and the complexities of planning and execution of the operation were definitely lessened when individual unit commanders were cognizant of the oceanographic picture. The rapid development of amphibious warfare caused the tactical picture to change too rapidly for rigid application of a science with which few persons were familiar. One of the results was that military commanders in coastal areas were confronted with oceanographic problems which they were not only unable to solve, but were frequently unable to formulate.

It is no secret that Army-Navy coordination leaves much to be desired. Military oceanography provides a common meeting ground, and military personnel aware of what can be accomplished are better prepared to recognize the problems of marine operations and assist in formulating a mutual strategy in harmony with the natural marine barriers. A special Military Oceanographic Service no more duplicates the functions of a parallel Naval Service than do other Army and Navy separate technical services.

A partial solution to the present situation appears to be found in an active liaison between professional oceanographers and regular military personnel. Since there are no longer established oceanographers in the regular military service, accomplishment of contracts with the established civilian oceanographic institutions is advisable as an economical means of training selected officers and for specific military research projects. If the proposed merging of Army and Navy into a single command is to accomplish improved coordination and cooperation, overlapping training of staff and combat officers need be accomplished. Oceanography is the science to contribute most to the intelligent perception of mutual problems so essential in joint staff planning of operations and in their execution.

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Contribution No. 363

DYNAMICS OF PRODUCTION IN A MARINE AREA

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Contribution on No. 363 Woods Hole Oceanographic Institution

TABLE OF CONTENTS

PAGE

INTRODUCTION 323

CONCEPTS OF PRODUCTION 323

  Standing Crop 324

  Material Removed 324

  Production Rate 325

PRODUCTION ON GEORGES BANK 328

SUMMARY 334

REFERENCES 334

DYNAMICS OF PRODUCTION IN A MARINE AREA

INTRODUCTION

During recent years increasing attention has been given to the factors which underlie the productivity of natural areas and special interest has begun to center on the quantitative aspects of the relations involved. When a more exact and critical approach to the dynamics of production is attempted, it becomes obvious that ecologists, both practical and theoretical, have considered productivity from so many entirely different points of view that confusion, both in the concepts and in the terminology, has resulted. Before considering the productivity of any particular area, a general delineation of the specific concepts involved is highly desirable, and an agreement on terms is necessary. The attempt to clarify the subject which follows was prepared after a lively and penetrating consideration of the matter by the participants in this symposium.

CONCEPTS OF PRODUCTION

All the ideas and measurements of productivity which have an ecological application, may be grouped under the following three fundamental concepts (Fig. 1):

Standing crop—the amount of organisms *existing* in the area at the time of observation.

Material removed—the amount of organisms *removed* from the area per unit time by man, or in other ways.

Production rate—the amount of organisms *formed* within the area per unit time.

All three of these major concepts of productivity are important, and are essential for a complete understanding of the operation of the area as an ecological complex. In addition, the quantities involved are to a certain extent mutually dependent.

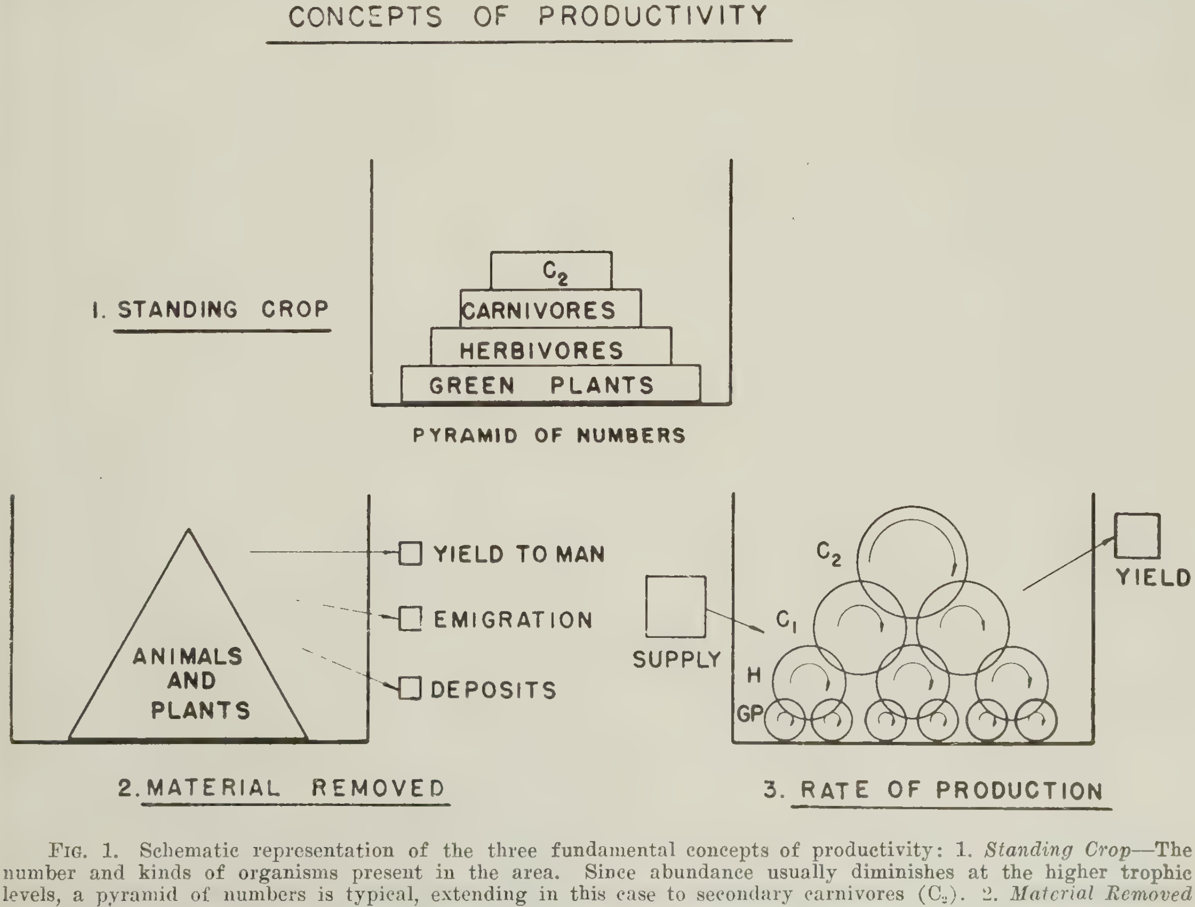

FIG. 1. Schematic representation of the three fundamental concepts of productivity: 1. *Standing Crop*—The number and kinds of organisms present in the area. Since abundance usually diminishes at the higher trophic levels, a pyramid of numbers is typical, extending in this case to secondary carnivores (C_2). 2. *Material Removed*—The organisms, or their parts, which are permanently removed from the area by man or in other ways. 3. *Rate of Production*—The rates at which organisms are formed within the area. The interdependencies of the green plants (GP), herbivores (H), and primary and secondary carnivores (C_1 and C_2) are indicated.

To avoid ambiguity in discussing the ecological relationships of the area, it is suggested that the terms "productivity" and "production" be not used in referring to the standing crop or to the material removed unless a phrase is added to make the meaning clear (Ivlev 1945). Measurements made under any of the three categories may be stated in terms of number of individuals, weight or "biomass," energy content, or any other characteristic (such as chlorophyll content) which may be adequate for the given situation. Evaluation on the basis of energy content has the advantage that the efficiency of the utilization of the incident solar radiation may be calculated directly.

STANDING CROP

Measurements of the standing crop, and hence of the concentration, of the various species inhabiting the area are essential in judging the harmful or beneficial effect of crowding within the species, and the effectiveness with which dependent species can feed upon forage species. When applied to the exploitation of a natural population by man, the magnitude of the standing crop similarly influences the size of the catch per unit effort. However, a knowledge of the standing crop does not give any information as to the time which has been required to produce the crop, or its replaceability.

To illustrate these points, the changes of population size with time for three hypothetical situations are represented diagrammatically in Figure 2. In the first situation the growth rate of the population is much more rapid than in the second, but conditions are such that the same size of standing crop is attained provided that the season is sufficiently long for the maximum value to be reached. In this case, the final size of the standing crop gives no information as to the rate of net increase. If, however, the standing crop is measured before the asymptotic level is approached, the situation with the more rapid increase will have the larger standing crop. The size of the standing crop at any time is the result of the summation of the excess of production over destruction from the beginning of the growth of the population to the moment of observation.

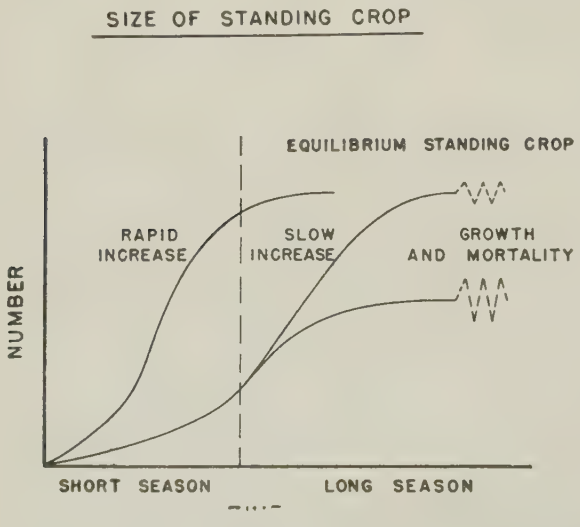

FIG. 2. Changes of population size with time in three hypothetical situations (for full explanation see text).

In the third hypothetical situation, the same length of time is required for the population to reach a maximum size as in the second situation, but the maximum level reached is lower. In both situations, the population may fluctuate above and below the average limiting value (broken lines at right of curves), and since equilibrium is being maintained, at least temporarily, the average rate of production must be exactly balanced by the average rate of destruction. If the population is measured by number of individuals, the birth rate will exactly equal the death rate, regardless of the length of life of the individuals (Pratt 1943). It is possible that in some cases the rates of production and destruction may be higher in the area with the smaller average standing crop. Therefore, the magnitude of the standing crop cannot be taken as a measure of the rate of production, just as the level of water in a tank gives no clue as to the rates of inflow and outflow.

Since we have seen that the actual size of the standing crop after equilibrium has been reached is not determined by the rate of net increase nor by the rate of production, it is clear that the factor, or factors, which limit the final size of the population must be external influences, such as the accumulation of metabolites, or the lack of food (Pratt, 1943). Although a large population can thus exist without its own rate of production being high, it may require a large amount of food for its maintenance. Therefore, the existence of a large standing crop at one trophic level does imply the existence of either a large initial crop of the organism or nutrient, on which it feeds, or of a high rate of production, or supply, of this material.

MATERIAL REMOVED

The material removed from an area may fall into several categories. In the first place, the amount of organisms harvested by man during a certain period may be measured and designated as the *yield.* In addition, other organisms may be permanently removed from the area by wind or currents, or by emigration accomplished by the organisms' own locomotion.[1] Organisms which grow in the area but which are consumed, or die in other ways, and decompose so as to enter the ecological cycle again within the same area are not considered to be a yield in the sense recommended here. However, dead organic matter which has become permanently inaccessible, as for example, if buried under bottom deposits, is an irrevocable loss to the system, and hence forms another subdivision of the material removed.

These different subdivisions have in common the fact that in each instance the particular material which is removed from the area does not return again to that area. The amounts of the yield to man and of the other subdivisions may be added together to form a total amount of material removed from the system for the period considered. It is obvious that neither the total material removed nor the yield to man can be maintained if it is greater than the supply of new material entering the area during the same interval, either in the form of nutrient substances or of immigrants. Because of the inevitable loss of materials (and energy) at each level in the food chain, the yield will ordinarily be much smaller than the supply. Measurement of the ratio of yield to supply, and hence the efficiency of the formation of the yield, is therefore of great importance to the ecologist, to the conservationist, and to the farmer or fisherman, in order to ascertain whether the actual yield represents a needlessly low utilization or an over-exploitation of the area.

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[1] This category may be also taken to include those organisms which are carried off by predators, other than man, provided that these predators do not form a functional part of the particular ecological unit being considered. Whether or not this limitation exists in any actual case may be difficult to decide.

The yield may, in some cases, be improved by increasing the supply of materials to the area, as for example through the use of fertilizers, but even without artificial enrichment the yield of a particular species may sometimes be increased by adjusting its numbers to the optimum level and by curtailing the amount of material removed from the area in other ways. The *maximum potential yield* is the largest maintained amount of a species which may be removed from the area per unit time under the best population and environmental conditions which could be maintained.

A knowledge of the standing crop and of the material removed will not provide an understanding of the fundamental dynamic equilibria within the community upon which the productivity of the area ultimately depends. For an adequate grasp of the factors controlling abundance and yield, it is necessary to ascertain also the rates of formation of the interdependent types of plants and animals in the area.

PRODUCTION RATE

The concept of the production rate as the amount of organisms formed per unit time (per unit area or volume) is complicated by the fact that in most natural areas organic matter is being formed or transformed at several trophic levels simultaneously, i.e., by the plants and animals of the food chain which depend upon one another. In order for measurements of production rate to be useful it is necessary to keep separate the values for the various trophic levels and in each case to distinguish between gross and net rates of formation (Lindeman 1942).

These trophic relations among the components of the production pyramid may be represented diagrammatically, first, for a situation in which the constructive and destructive processes are equal so that there is no gain or loss in the amounts of organisms present at the end of the period over that at the beginning (Fig. 3). The amounts of energy contained in the organisms in the area at the beginning of the period, i.e., the standing crop, are indicated by the rectangles at the left of the diagram. The rectangles at the right represent the amounts of energy absorbed at each trophic level and show *qualitatively* the transformations which the various portions undergo during the period. For simplicity only three trophic levels are indicated. Similar transformations could be added for secondary and tertiary carnivores, for parasites, and for saprophytes.

In tracing the energy and material through the production pyramid we may start with the incident light which falls upon the area. A portion of this light (small, in the aquatic environment) reaches the plant cells and is absorbed by them. A small portion of the absorbed energy appears as the carbohydrate which has been formed by photosynthesis (P_1). The amount of material produced by this anabolic process (or of the energy represented) is termed the *gross plant production*. It has also been called the *primary production* because the animal substances which result from consuming the plants, and each other, are transformations of the original plant material, and thus represent alternative forms of the same material (and energy). In this sense the gross plant production may be considered a measure of the "total production" of the area, but because of the obvious ambiguity the latter term should be avoided. A large part of the gross production is lost as the result of catabolic processes. This loss may be measured by the amount of respiration. The remaining fraction of the gross production accounts for the new plant growth (P_2) and this is termed the *net plant production,* or simply, the *plant production,* for unit area and time (cf. Riley, 1941a).

Since in the case considered there is no permanent increase or decrease in plant material, all of this new plant growth is destroyed and the energy transformed before the end of the period. Part of the plant material produced is consumed by herbivores and the remainder dies in some other manner and decomposes. In many situations a large proportion of the plant material consumed is not assimilated by the herbivores, but is passed through the gut undigested. This fraction (U) may be added to that which has decomposed following destruction in other ways.

A similar analysis may be made of the material which enters into each of the successive trophic levels represented by the animals and colorless plants. At the herbivore level we start with the amount (or energy) of the food assimilated (P_1), but much of this is lost in catabolic processes and the material which appears as the actual growth of the herbivore population (P_2) is termed the *herbivore production.* It is assumed in this case that the herbivores are entirely destroyed during the period either by the carnivores or by death and decomposition from other causes. The same processes occur at the carnivore level with a resulting *carnivore production* for the period. The loss of the carnivore material at the top of the pyramid will of course all be accounted for by decomposition since none is consumed by predators.

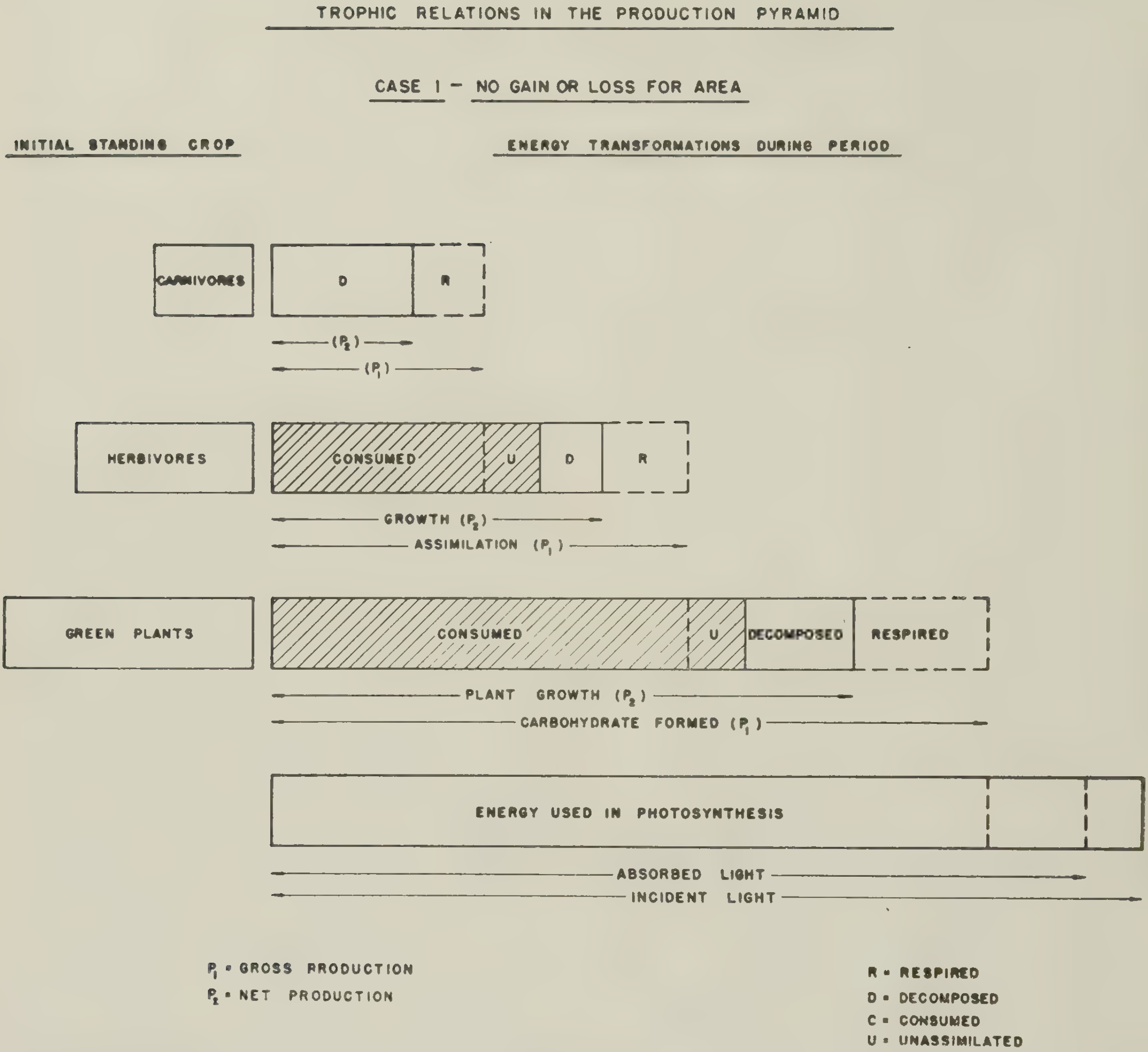

TROPHIC RELATIONS IN THE PRODUCTION PYRAMID
CASE 1 – NO GAIN OR LOSS FOR AREA
INITIAL STANDING CROP
ENERGY TRANSFORMATIONS DURING PERIOD
CARNIVORES
D
R
(P2)
(P1)
HERBIVORES
CONSUMED
U
D
R
GROWTH (P2)
ASSIMILATION (P1)
GREEN PLANTS
CONSUMED
U
DECOMPOSED
RESPIRED
PLANT GROWTH (P2)
CARBOHYDRATE FORMED (P1)
ENERGY USED IN PHOTOSYNTHESIS
ABSORBED LIGHT
INCIDENT LIGHT
P1 = GROSS PRODUCTION
P2 = NET PRODUCTION
R = RESPIRED
D = DECOMPOSED
C = CONSUMED
U = UNASSIMILATED

Fig. 3. Trophic relations in the production pyramid—Case 1: Relations shown qualitatively for a situation in which there is no net increase or decrease (see text).

At the end of the period for this hypothetical case of complete equilibrium the standing crop is of exactly the same magnitude as at the beginning and there has obviously been no yield. Production has been going on, however, at definite rates at the various levels, and in this case destruction of the materials has exactly balanced their formation during the period. The wheels of the factory have been turning but the products of the machinery have been taken in again as raw materials. Nevertheless for a critical understanding of the area it is essential for the ecologist to know what wheels are turning and at what rates. The magnitude of the standing crop at any moment does not give a measure of the rate at which production is going on since it is determined by the difference between the rates of production and destruction over the whole previous history of the population up to the time considered.

Let us consider now a second case, in which smaller amounts of organisms are destroyed than are formed during the period (Fig. 4). Under these circumstances the growth (P_2) of any one of the categories of organisms would be accounted for at the end of the period in three ways: one portion consumed, one portion decomposed, and one portion remaining in existence and representing an increment which may be termed the *net increase* (P_3). The standing crop at the end of the period is consequently larger than at the beginning of the period by the amount of the net increase. In a situation in which the amount of destruction during the period was greater than the amount of production, the net increase (P_3) would be negative, and the standing crop would be reduced.

If this surplus material is permanently removed from the system by man, it will constitute a yield. Obviously these organisms could not continue to be removed from the system in succeeding periods unless

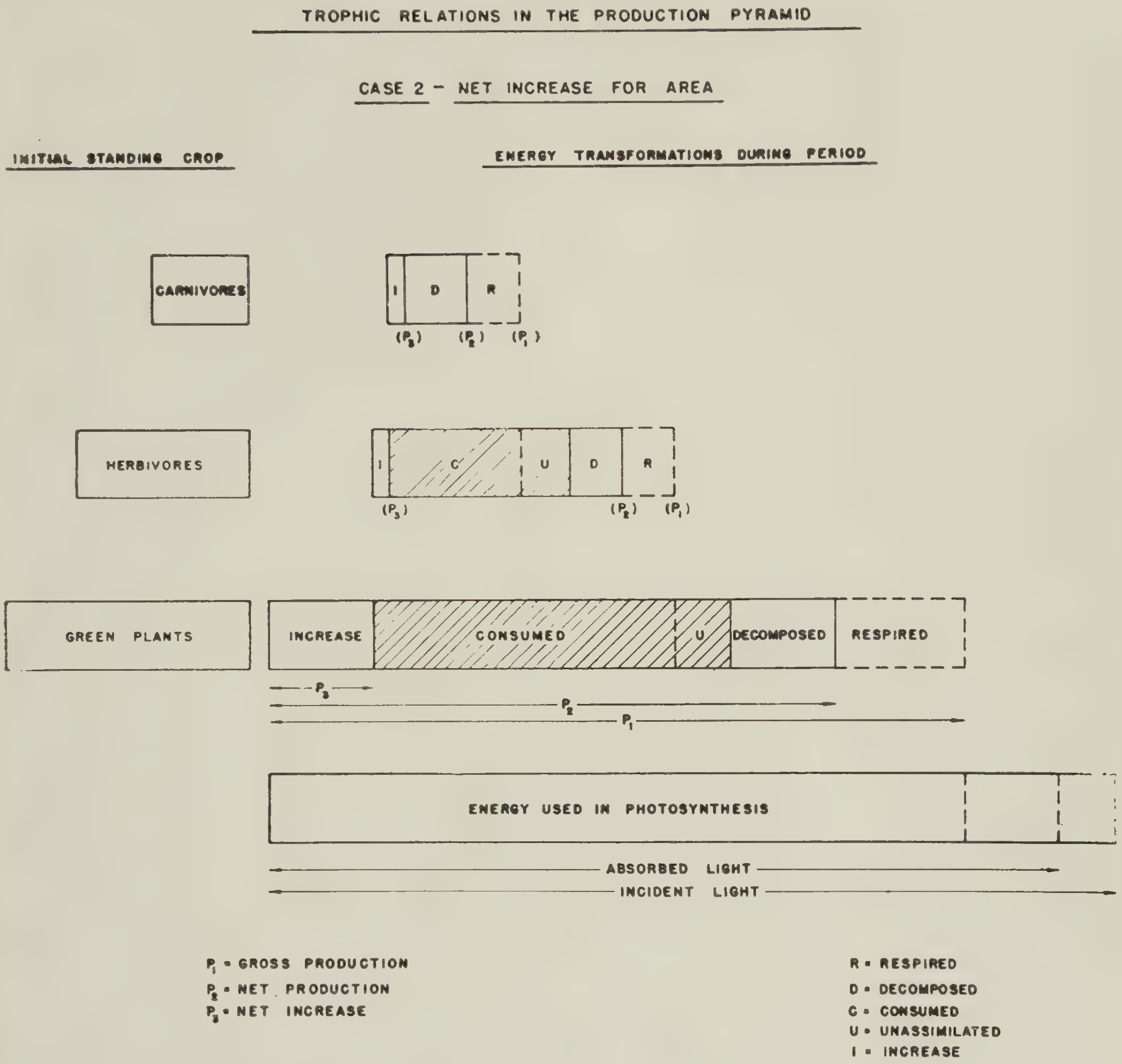

TROPHIC RELATIONS IN THE PRODUCTION PYRAMID
CASE 2 – NET INCREASE FOR AREA
INITIAL STANDING CROP
ENERGY TRANSFORMATIONS DURING PERIOD
CARNIVORES
I
D
R
(P_3)
(P_2)
(P_1)
HERBIVORES
I
C
U
D
R
(P_3)
(P_2)
(P_1)
GREEN PLANTS
INCREASE
CONSUMED
U
DECOMPOSED
RESPIRED
P_3
P_2
P_1
ENERGY USED IN PHOTOSYNTHESIS
ABSORBED LIGHT
INCIDENT LIGHT
P_1 = GROSS PRODUCTION
P_2 = NET PRODUCTION
P_3 = NET INCREASE
R = RESPIRED
D = DECOMPOSED
C = CONSUMED
U = UNASSIMILATED
I = INCREASE

FIG. 4. Trophic relations in the production pyramid—Case 2: Relations shown qualitatively for a situation in which there is a net increase (see text).

an equal amount of material, as nutrients or in some other form, were added each period. If the organisms representing the net increase are not removed from the system, and if circumstances are such that they can continue in existence in the area, there will be a permanent increase in the size of the standing crop. Again, this can take place only to the extent to which an equivalent supply of nutrients or other materials are added to the area. The standing crops of lakes are frequently seen to increase in this way with the result that the lakes become more eutrophic and the process is known as *eutrophication.*

In the discussion of production rate thus far nothing has been said about the length of the period considered. The time required for each type of organism to complete its growth, to die and decompose, and to start the cycle over again is known as its period of *turnover.* The length of the turnover period usually differs widely for the organisms at the different trophic levels of the production pyramid, and may differ for the same level in different situations and at different seasons of the year. The green plants of a terrestrial area may have essentially only one turnover per year, whereas the phytoplankton of an aquatic area may turnover within short periods varying widely from a few days to several weeks. In the latter case the same material may be used over again several times during the year, and it would thus have little meaning to add up the increments of growth for the whole year in an attempt to reach a "total" annual value. If the growth of the plants is measured as energy, it is permissible to summate the amount of energy which has been transformed during the year since the energy can be used by the plants only once. A comparison may thus be made between the annual incident radiation and the energy content of the plants produced.

In the case of the organisms at successively higher trophic levels, both the materials and the energy are used over again one or more times. A summation of amounts of production at all trophic levels for a long period, such as a year, therefore similarly has little meaning. (Thienemann 1931).

The procuring of significant measurements of production rate is further complicated by the fact that growth, consumption, and decomposition may all be going on simultaneously under certain circumstances, as is frequently seen in aquatic situations. This difficulty may be dealt with by reducing the period considered to such a small size that instantaneous rates of growth, decomposition, etc., are obtained, or in other words by obtaining the differentials of the curves describing these processes. Production is therefore best measured as a set of rates applying to the gross production, net production, and net increase for each category of organisms or each trophic level. The term "productivity" has sometimes been used specifically for the rate at which assimilation (gross productivity) or growth (net productivity) is taking place since it is a measure of the rate at which the wheels of the system are turning. In view of the fact that this term is used in various broader senses to describe the capacity of an area to produce, it is preferable to employ the more explicit term, "production rate," and to specify the units of time and area considered. A mathematical development of these considerations is presented in the Appendix.

In cases in which the magnitudes of the rates of production at the different trophic levels can be measured, calculations may be made of the quantitative relationships of the various steps in the production. The following ratios, or efficiencies, are of interest (symbols refer to Fig. 4):

For the plant:

$$\text{Absorption} = \frac{\text{absorbed light}}{\text{incident light}}$$

$$\text{Assimilation} = \frac{\text{carbohydrates formed}}{\text{absorbed light}}$$

$$\text{Growth} = \frac{\text{plant growth } (P_2)}{\text{carbohydrates formed } (P_1)}$$

$$\text{Increase} = \frac{\text{net increase of plants } (P_3)}{\text{plant growth } (P_2)}$$

For the herbivore:

$$\text{Consumption} = \frac{\text{plants consumed (C including U)}}{\text{plant growth } (P_2)}$$

$$\text{Assimilation} = \frac{\text{plants assimilated (C excluding U)}}{\text{plants consumed (C including U)}}$$

$$\text{Growth} = \frac{\text{herbivore growth } (P_2)}{\text{herbivore assimilation } (P_1)}$$

$$\text{Increase} = \frac{\text{net increase for herbivore } (P_3)}{\text{herbivore growth } (P_2)}$$

For the carnivore:

$$\text{Consumption} = \frac{\text{herbivores consumed (C including U)}}{\text{herbivore growth } (P_2)}$$

$$\text{Assimilation} = \frac{\text{herbivores assimilated (C excluding U)}}{\text{herbivores consumed (C including U)}}$$

$$\text{Growth} = \frac{\text{carnivore growth } (P_2)}{\text{carnivore assimilation } (P_1)}$$

$$\text{Increase} = \frac{\text{net increase for carnivore } (P_3)}{\text{carnivore growth } (P_2)}$$

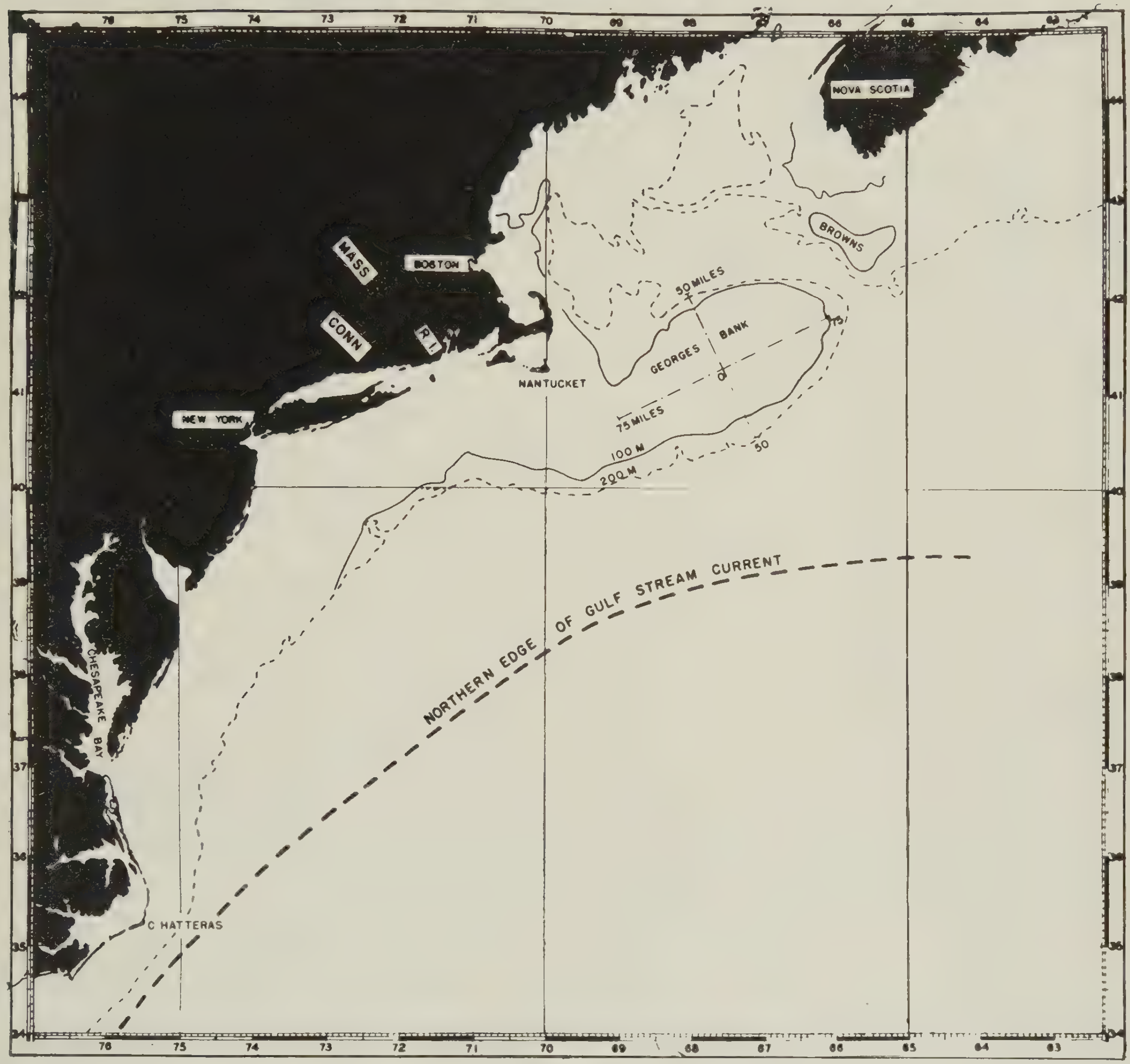
The efficiencies given above are for the rates of the several processes at each of the trophic levels. Overall efficiencies may also be calculated, such as the ratio of the growth rate at one level to the growth rate at a previous level. Efficiencies for the growth or the net increase at any level based on the ratios of the energy content of the products to the incident radiation may also be found. On occasion it may be desirable to determine the ratios of assimilation, growth, net increase, etc., to the size of the existing standing crop. Similarly, the ratio of the rate at which the animals consume their food to the abundance of the food may be found instead of the ratio to the growth of the food.

The foregoing analysis of the processes involved in production no doubt will appear as an over-simplification. The material is intended, however, merely as a framework to assist in clarifying the fundamental relationships in a natural area and in placing them more readily on a quantitative basis. Illustrations of the use of these concepts of the dynamics of production will be found in the following section of the present paper and in the succeeding papers of this symposium (Pennak 1946, Edmondson 1946, and Ricker 1946).

PRODUCTION ON GEORGES BANK

The application of the foregoing concepts of productivity to a marine situation may now be illustrated for Georges Bank, an important fishing area off Cape Cod (Fig. 5). The size and relative inaccessibility of an offshore area of this sort render difficult the procuring of adequate information. As a result only a preliminary idea of the quantitative relationships can as yet be formed for Georges Bank although a very considerable number of biological and physical observations have been made. My present purpose is to point out the nature of the fundamental factors in a situation such as Georges Bank, and to consider the influence of special environmental conditions, such as the movement of water, in controlling the dynamics of production.

The chief components and interdependencies of Georges Bank are represented diagrammatically in Fig. 6. The green plants at the base of the production pyramid are the phytoplankton, and of these the diatoms are the most important. The herbivores, which constitute the next trophic level, are composed chiefly of planktonic crustacea. The copepods are generally the most prominent of the diatom-eating crustacea, but certain types of the larger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65
64
63
NOVA SCOTIA
BROWNS
MASS
BOSTON
CONN
R. I.
NANTUCKET
NEW YORK
50 MILES
GEORGES BANK
75 MILES
100 M
200 M
50
NORTHERN EDGE OF GULF STREAM CURRENT
CHESAPEAKE BAY
C HATTERAS
42
41
40
37
36
35

FIG. 5. Location and dimensions of Georges Bank.

crustacea may also feed directly on the diatoms. The benthos obtains its food either directly from the phytoplankton, or indirectly by way of the detritus. Some bottom forms and some of the larger plankton forms, such as Sagitta, may feed extensively on the copepods and thus constitute a third trophic level. The various species of fish on Georges Bank, which depend upon the zooplankton, the benthos, or upon each other, form one or more additional trophic levels among the carnivores.

Let us consider first the circumstances in a marine area which affect the utilization of solar energy for the photosynthesis of the diatoms. The energy available is determined by the amount of solar radiation incident upon the sea surface minus that portion which is lost by reflection and by the absorption of the light by water and by particles other than the plant cells. In the region of Georges Bank the average energy per unit area reaching the sea surface for each month is shown in Table 1. These values are the monthly averages of the illumination which fluctuates each day from zero to the maximum reached at noon. The reduction in incident light with depth, due to absorption by the water and by dissolved and suspended material, has been measured by means of the protronic photometer and the Secchi disc (Clarke 1939a). Diatoms themselves may become sufficiently abundant to cause a significant decrease in transparency. The extent to which the plant cells may thus cut off their own light is shown by the relation between the Secchi disc measurements from eleven cruises to Georges Bank and the abundance of phytoplankton (Fig. 7). In all cases in which the plant pigments exceeded 40,000 Harvey Units per m^3 the Secchi disc depth was found to be reduced to 8 m or less.

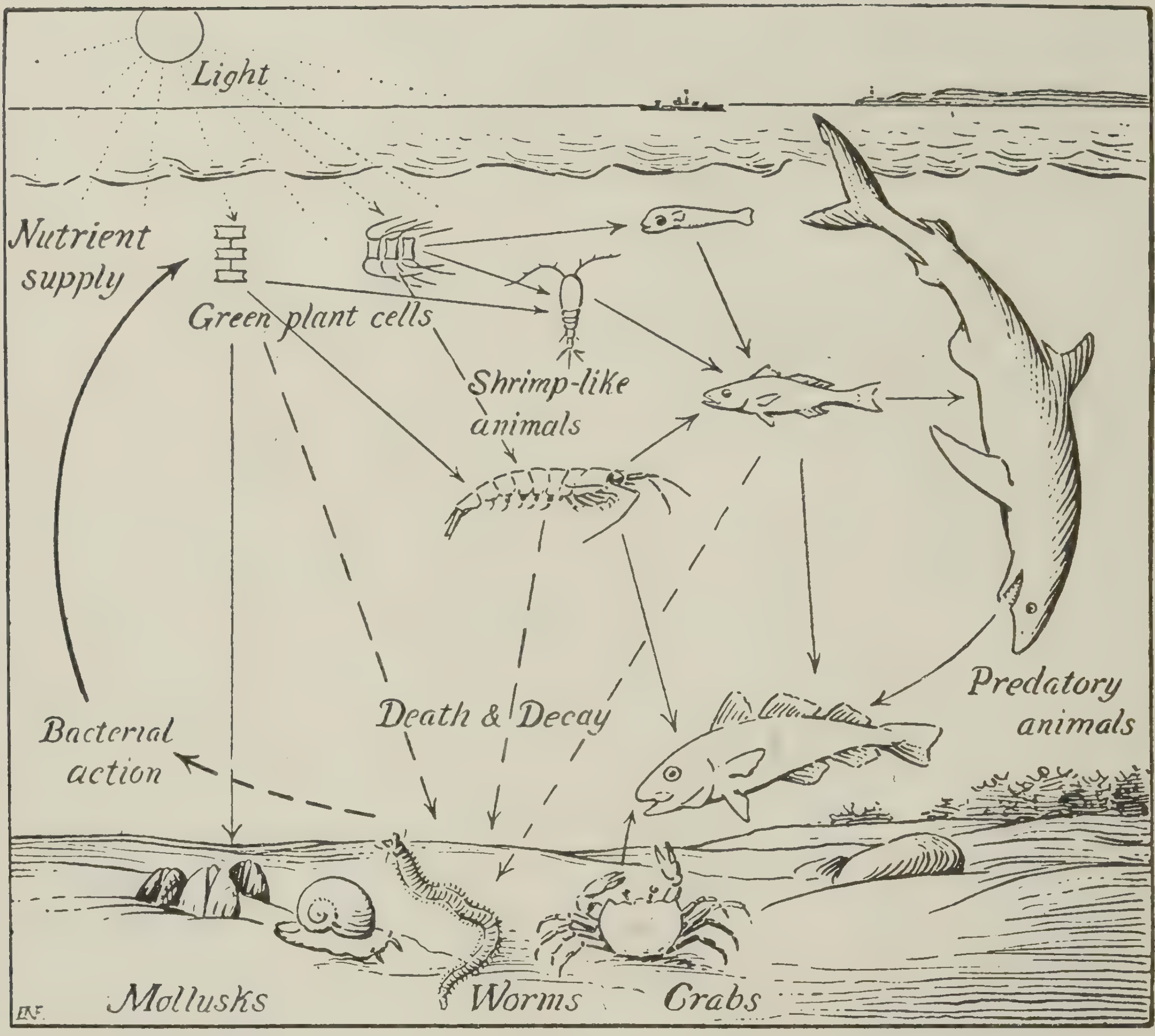

FIG. 6. Diagrammatic representation of the components of the production cycle in a marine area. (After Clarke, from ''Science from Shipboard,'' Science Service, 1943.)

If we employ a value of .0017 g cal/cm^2/min as an approximation for the compensation intensity[2] for marine diatoms (Jenkin 1937; Pettersson *et al.* 1934), we may calculate the maximum and minimum depths at which such an illumination would be found using the different transparencies found for the bank water and the various monthly averages for the light at the surface. If we assume that values based on the average illumination may be taken as rough approximations of the average position of the compensation point, the depths shown in the right hand columns of Table 1 give the limits down to which constructive plant growth can take place. Plant growth is thus clearly seen to be limited to a stratum far shallower than the depth of water over the main portion of Georges Bank. It is obvious that there would not be sufficient light to support plants attached to the bottom except in the region of the Shoals and there the shifting sand would not permit attachment.

A second factor of concern in a marine area and one having especial importance on Georges Bank is the action of vertical mixing. Tidal currents over the bank prevent the water from becoming stratified even in summer and extensive vertical mixing takes place at all seasons. So complete is this process that there is little difference in temperature or salinity from surface to bottom over the whole of the central portion of the bank at any time during the year (Fig. 8). The turbulence of the bank water causes a vertical translocation of the diatoms which prevents their becoming adapted to any one condition of illumination and in addition carries them to levels below the compensation depth for a portion of the day. This harmful effect of vertical mixing on the utilization of light by the plant cells is perhaps counterbalanced to some extent by the

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[2] The compensation intensity is the intensity of light at which the rate of photosynthesis is just equal to the rate of respiration. At illuminations below the compensation intensity no constructive growth of the plant cell can take place.

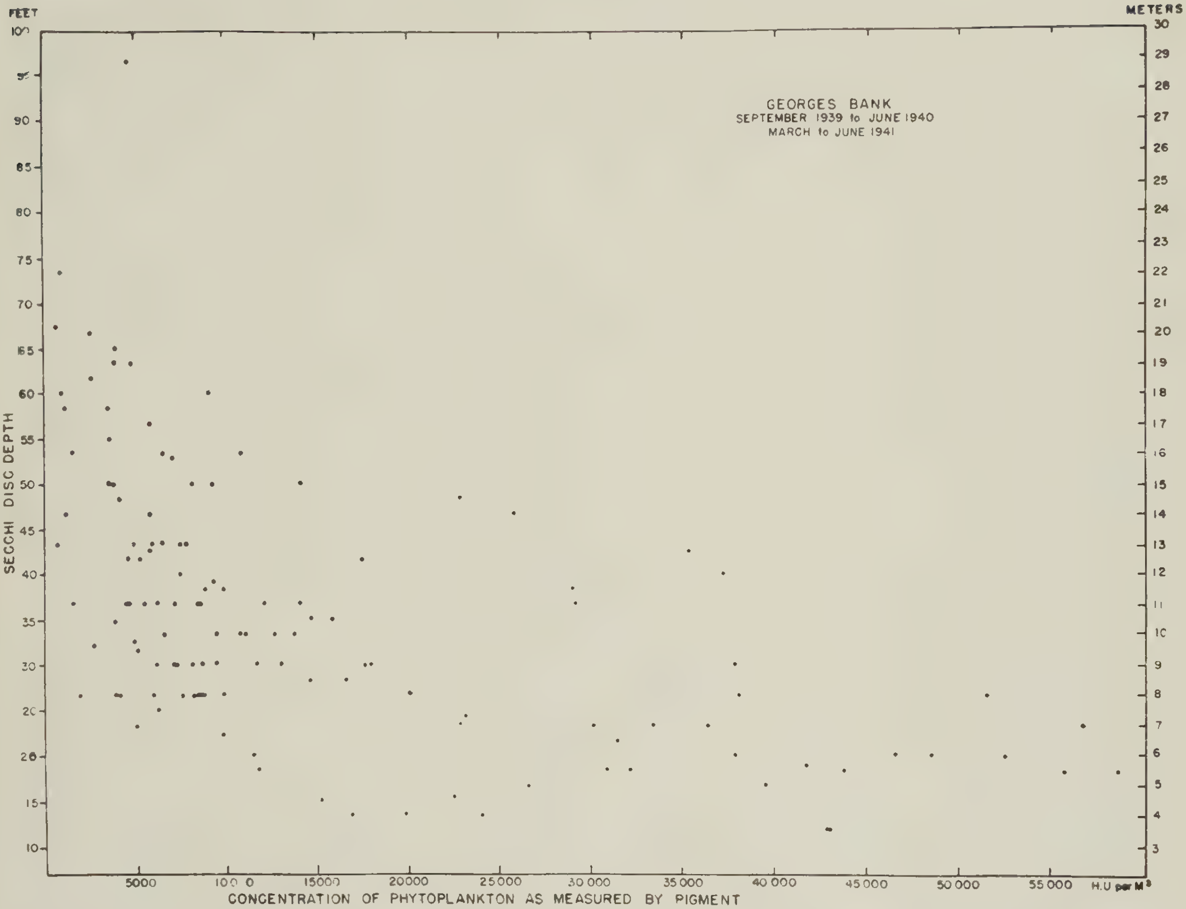

FIG. 7. Influence of phytoplankton abundance on the transparency of the water. Phytoplankton measured as Harvey Units per m3 and transparency determined by Secchi disc depth (representing an average reduction of the illumination to 15% of its value at the surface).

action of the vertical movements in restoring water rich in nutrients to the upper layers. Little is known of the rate of this vertical transport for a situation such as Georges Bank and its measurement constitutes one of the most needed observations.

As far as our present information goes, it seems probable that the chief factor limiting the growth of the diatoms on Georges Bank during late autumn, winter, and early spring is the lack of sufficient illumination caused by the lower solar radiation and the higher degree of vertical turbulence. During the remainder of the year, when illumination is adequate, the lack of nutrients, the high temperature causing increased respiration, and the consumption by herbivores are considered to be the chief limiting factors (Riley, 1941b). The rate at which the herbivores consume the phytoplankton is difficult to determine but recent experiments and calculations strongly indicate that the grazing activity of copepods may constitute the chief agent for the reduction of the diatom population at times. (Fuller & Clarke 1936, Fuller 1937, Harvey 1937, Riley 1946).

The next step in the food cycle of a marine area

TABLE 1. *Compensation Depths for Georges Bank.*

Values for radiation are the average for each month (Sverdrup, Johnson, and Fleming. 1942, Table 25 after Kimball). Maximum and minimum Secchi disc depths are for all stations within the 200 m. contour; the average Secchi disc depths are for all stations within the central area of mixed water. The depths at which the compensation intensity (.0017 g. cal /cm² /min.) occurred were obtained from the Secchi disc depths, assuming the latter to represent a reduction of illumination to 15% (Clarke 1941).

Month	Incident Radiation g. cal/cm²/min.	Secchi Disc			Compensation Depth		
		Max. m.	Min. m.	Ave. m.	Max. m.	Min. m.	Ave. m.
January	.094	20	7	14	42	15	30
February	.138	..	..	..	..	..	..
March	.212	17	5.5	9	43	14	22
April	.272	8	3.5	5	21	9	14
May	.306	18	3.5	7	49	10	19
June	.329	22	4.5	11	59	12	30
July	.302	..	..	..	..	..	..
August	.267	..	..	..	..	..	..
September	.230	18	6	8	47	15	21
October	.174	..	..	..	..	..	..
November	.115	..	..	..	..	..	..
December	.086	..	..	..	..	..	..

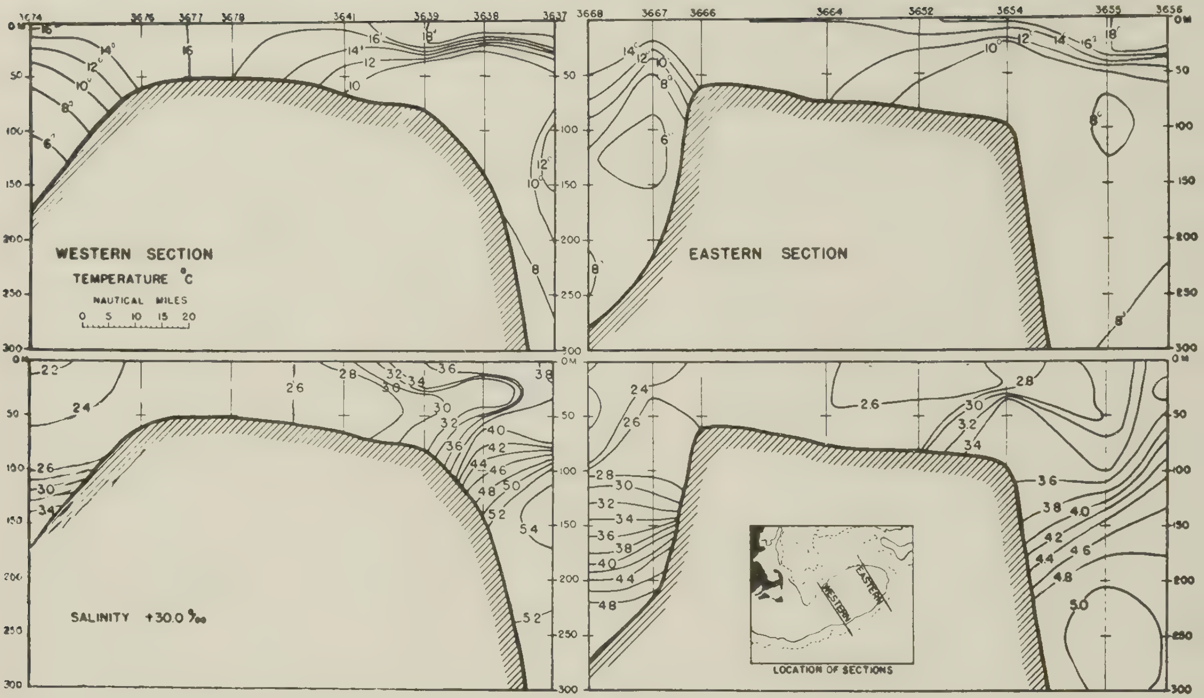

Fig. 8. Vertical sections showing the homogeneity of the water over Georges Bank. The contour of the bank is indicated by the crosshatching from the Gulf of Maine on the left to the edge of the Continental Shelf on the right. Station numbers for the cruise of September, 1939, appear at the top of the diagrams.

is the production of herbivores and we have seen that the copepods are the chief planktonic form at this trophic level on Georges Bank. It is obvious that the growth of the copepod population is dependent upon the availability, at the right time, of food which is of a suitable type and supplied in adequate amounts. Opinions differ, however, as to the nature and quantitative relations of the dependence of copepods upon diatoms (Clarke 1939c), and further investigation of these critical points is highly desirable. Values have been obtained for the seasonal increase and decrease in the standing crop of zooplankton on Georges Bank from our extensive surveys of the area, and for certain species the occurrence of reproductive periods has been determined (Clarke, Pierce, & Bumpus 1943). However, estimates of the food requirements of copepods based on laboratory tests vary widely, and we have little direct knowledge of the control of breeding and growth by the type and abundance of food. (Marshall, Nicholls, & Orr 1934, 1935; Clarke & Gellis 1935; Clarke & Bonnet 1939; Raymont & Gross 1942).

Another important influence controlling the abundance and the distribution of zooplankton is the action of horizontal currents. The bubble of mixed water overlying Georges Bank prevents the coastal current from sweeping across the bank and forces the water flowing out of the Gulf of Maine to circulate in a clockwise direction around the margin of the bank (Redfield, 1941). The mixed bank water, with its contained fauna and flora, thus tends to persist with a certain degree of isolation. Outside water with different populations at times encroaches upon Georges Bank, and on other occasions segments of the bank water are drawn off, perhaps seriously decimating the communities of plants and animals which are dependent upon the bank environment (Walford 1939, Iselin 1939). A quantitative evaluation of the periods and amounts of these exchanges with the water beyond the margins of Georges Bank is seriously needed. The abundance of the plankton on the bank may be due in some cases both to accumulation brought about by currents and to an environment which is favorable for their vigorous growth. Such dual action has been clearly indicated in the control of the population of certain species of copepoda and sagittae (Clarke, Pierce, & Bumpus 1943).

It is certain that the benthos plays an important part in the food cycle of Georges Bank, since the cod and haddock, which bulk the largest in the commercial catch of fish, are bottom feeders. We have no quantitatively reliable information, however, on the size of the standing crop of the various components of the bottom fauna, to say nothing of their rates of production. This information is sorely needed. Another prominent category of animals, which appears to be partly associated with the bottom and partly pelagic, is composed of the larger planktonic crustacea. The biomass of these organisms has been found to average about half that represented by the smaller zooplankton, but in certain stages of their development and in certain areas they may become very abundant (Whiteley 1946). There has been no opportunity as yet to ascertain what importance these larger crustacea may have in the food cycle of the bank.

Our knowledge of the quantative relations of the fish at the top of the production pyramid is limited to statistics derived from the landings of commercial species. These data give us valuable information on the yield of fish from the area but knowledge of the standing crop and of the rates of production can be obtained only indirectly by means of calculations based on, as yet, unconfirmed assumptions.

Although there are so many vital gaps in our understanding of the various aspects of production in an area such as Georges Bank, it is desirable to bring together such data as have been obtained up to the present. The chief constituents and interdependencies of the ecological cycle on the bank, with approximate values representing our present knowledge of their quantitative relations, are shown schematically in Fig. 9. The diagram indicates that nutrients are provided by regeneration within the area but must also be brought into the area by currents, although the extent of this supply is not known. Currents also may bring in certain elements of the zooplankton and on occasion may account for an important loss of the permanent plankton, of the larvae of the benthos, and of the eggs and young stages of fish. A certain amount of migration of fish to and from the bank undoubtedly takes place, but our general knowledge of the fishery indicates that it is usually not important quantitatively.

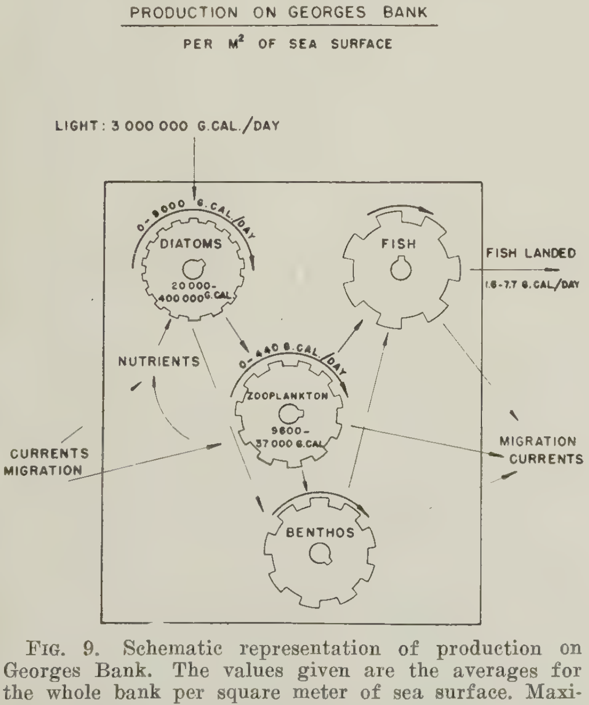

FIG. 9. Schematic representation of production on Georges Bank. The values given are the averages for the whole bank per square meter of sea surface. Maximum and minimum values within the cogwheels are for the standing crop, those over the wheels are for net production rate. Yield is indicated at right. For full explanation see text.

The maximum and minimum values for the average standing crop of diatoms and of zooplankton over the whole of Georges Bank have been calculated in terms of g cal. per square meter (Riley 1941b, Clarke 1939b) and are shown within the cogwheels in the diagram. One cc. of zooplankton was found to be equal to 1 g wet weight or 0.1 g dry weight, and equivalent to 400 g cal of energy. Adequate quantitative data exist neither for the abundance nor growth of the benthos. For the fish, however, estimates based on the landings and recruitment of the haddock (which usually comprise the major portion of the commercial catch) during the early 1930's suggest that the standing crop of market-sized fish at the beginning of the year might be no greater than twice the amount of the landings during the year (W. C. Herrington, private communication.)

The rates of net production are indicated schematically in the diagram as the rates at which the cogwheels are turning. In the case of the diatoms (Riley 1941b) and zooplankton[3] the rates vary from zero during the months of the year when no growth is taking place, to the approximate maximum values shown (averages for the whole bank). In the absence of actual data on the growth rates of the fish, the average daily value for the fish landed during the whole year may be used as a very rough minimum value for net production.

This preliminary picture for Georges Bank indicates a pyramid of abundance and a pyramid of production rates which diminish sharply toward the higher trophic levels. According to these very approximate values, the 3 million g cal of energy which fall on each square meter of sea surface per day on Georges Bank, as an average for the year, would be used by the diatoms with a maximum efficiency of about 0.3%. The production of zooplankton represents a maximum efficiency of about 0.015%.

The low value for the efficiency of the production of phytoplankton in a marine area is due in part to the inefficiency of the process of photosynthesis itself and in part to the fact that only a small fraction of the light incident on the sea surface can be absorbed by the plant cells because a large part of the radiation is removed by the water medium. Fresh-water phytoplankton has been found by Manning to produce carbohydrate under natural conditions with an average efficiency of 2.7% of the light absorbed (Clarke 1939a). Since in a series of Wisconsin lakes only 1.6% to 14% of the light incident on the lake was absorbed by the plant cells, the over-all efficiency of gross plant production in the utilization of solar energy ranged from 0.043% to 0.38% in these cases. In Long Island Sound the efficiency of gross plant production appeared to be about 0.55% to 0.82% and the estimated mean efficiency of net plant production was 0.31% (Riley 1941a). These values are in satisfactory agreement with the corresponding determinations for Georges Bank (Riley 1941b).

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[3] Clarke (Unpublished data). A value for the maximum production rate of the zooplankton was approximated by finding the average daily increment in the standing crop for the period of most rapid growth (April).

It is of interest to compare the foregoing calculations with similar determinations undertaken for terrestrial plants. Plants on land enjoy the initial advantage that they can absorb the major portion of the incident radiation when the vegetation completely covers the ground. Values for the production of various types of the earth's vegetation have been summarized by Riley (1944) with an estimate for the average yearly efficiency of gross production for terrestrial plants of about 0.09%, and a maximum value, obtained in the best forests, of about 0.25% (Krogh 1934). When the calculations are limited to the growing season, higher efficiencies are to be expected. Corn grown for 100 days in Ohio under the best conditions produced a dry weight of 13,200 lbs./acre for the whole plants, or 4,750 lbs./acre for the grain alone, representing a maximum yield of 100 bushels of grain per acre (Transeau 1926). When the respiration loss is added, the former value is equivalent to a gross production of 74,000 g cal/m^2/day, or an efficiency for gross plant production of 1.6%, and for net plant production of 1.2%. These efficiencies are noticeably higher than the maximum observed on Georges Bank.

The weight of whole fish of all species landed annually from Georges Bank (area about 10 million acres) from 1923 to 1945 ranged from a minimum of 63 million lbs. in 1934 to a maximum of 289 million lbs. in 1929. This represents a yield of 7 to 33 lbs./acre/year, which is equivalent to 1.6 to 7.7 g cal/m^2/day (assuming an energy content of 740 g cal/g for raw, fresh fish)[4] or an efficiency of utilization of the average incident radiation of .00005% to .00025%. This yield is similar to that of 19 lbs./acre/year calculated by Juday (1940) for Lake Mendota but is considerably less than values for the animal products of cultivated land which may give yields for cattle and sheep of 150 lbs./acre/year (Graham 1944). The fact that cattle and sheep are herbivorous animals with only two links in their food chain, gives them an advantage over commercial species of fish which may be secondary or tertiary carnivores. Fertilized fresh-water ponds in the Southeast will support a standing crop of about 600 lbs. of fish per acre and will give a yield of about 300 lbs./acre/year. (Swingle & Smith 1941, 1942).

If the dynamics of production in a marine area result in an efficiency which seems discouragingly low, it should nevertheless be borne in mind that for an area like Georges Bank man is required to expend no effort in cultivation and that renewed fertilization is automatically provided. Thus if the bank is exploited intelligently, it can provide a valuable crop for an indefinite period.

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[4] Taken from the table of Composition and Value of Food in the Handbook of Chemistry and Physics. Chemical Rubber Publishing Co., 1944, p. 1458.

SUMMARY

A consideration of the productivity of a natural area should involve the concepts of (1) standing crop, (2) material removed, including the yield to man, and (3) the production rate. The production rate of the organisms at different trophic levels should be considered separately and distinction made between gross production (assimilation), net production (growth), and net increase in the standing crop per unit time. Diagrams are presented illustrating the interrelations between the processes of production, consumption, and decomposition at the various levels in the ecological complex.

The application of the foregoing concepts to a marine area is illustrated using data from Georges Bank. The nature of the fundamental factors underlying the productivity of the bank is pointed out with a consideration of the quantitative relationships insofar as the existing measurements permit. Values for the standing crop and for the net production of the phytoplankton and the zooplankton are presented with a discussion of the controlling influence of the reduction of light in the water and of the dislocations due to currents. Values for the yield of the commercial catch of fish from the bank are compared with yields obtained from fresh-water and terrestrial areas.

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Report of the years 1943, 1944, 1945

THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

REPORT FOR THE YEARS
1943, 1944, 1945

TABLE OF CONTENTS

PAGE

I Trustees, as of January 1, 1946 3

II Members of the Corporation, as of January 1, 1946 4

III Reports of the Treasurer 5

IV Report of the Director 15

V Staff, as of December 31, 1945 35

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Albert E. Parr, American Museum of Natural History, New York, N. Y.
Elihu Root, Jr., 31 Nassau Street, New York, N. Y.

Ex Officio

Columbus O'D. Iselin, Woods Hole Oceanographic Institution, Woods Hole, Mass.
Lawrason Riggs, 120 Broadway, New York, N. Y.

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III. REPORTS OF THE TREASURER

To the Members and the Trustees of the
Woods Hole Oceanographic Institution:

Gentlemen:

1943

The accounts for the year 1943 have been audited by Messrs. Stagg, Mather & Hough, public accountants.

During the year bonds costing $132,190 were redeemed at a net profit of $3,002.88 (after adding applicable reserve for amortization). There was invested during the year in bonds $37,112.50 and in stocks $8,856.93. Uninvested cash at the end of the year in endowment fund was $94,362.56, which was invested shortly thereafter.

In addition to the amount of $27,168.51 due from the General Account to the Special Income account at the end of 1942, there was withheld during the year further special income of $2,688.75 plus an adjustment of $23.50, making a total of $29,880.76 due this fund at the end of 1943. The continued holding of these funds due Special Income in the General Fund was necessitated by the unavoidable delay in the payment of the vouchers on Government projects.

The indebtedness of the Government to the Institution increased from $69,335.10 at the end of 1942 to $233,642.75 at the end of 1943. Of this amount all but about $500 had been received from the Government prior to the date of this report. This indebtedness is, however, claimed to be subject to a refund to the Government of $15,838.82. There was spent for the account of the Government during the year $464,303.34, in addition to which overhead allowances, calculated in accordance with the provisions of the contracts with the Office of Scientific Research and Development in the amount of $98,639.49, were charged to the Government, of which, however, $15,838.82 may be subject to refund, as above stated.

The net loss on the contracts from the Bureau of Ships paid out of our own income was $7,205.76.

On account of the lack of cash, due to financing of the Government contracts, the appropriation of $4,800 from the General Fund to the Reserve for Periodic Replacements had not been transferred at the end of the year and is still due from the General Fund to that Reserve Fund. At the end of the year that fund consisted of

Bonds of the book value of	$17,195.00
(Market value of $17,327.50)	
Cash	31,463.18
Indebtedness from General Fund	4,800.00
	$53,458.18

The total income of the Institution from its endowment funds after the payment of custodian fees, was $111,540.78. The total expenditures, excluding direct contract expenditures for the Government and including the loss on the Bureau of Ships contracts, amounted to $129,831.76. Reducing this by the sum of $82,800.67, being the net amount allocable to overhead expenses chargeable to the Government, leaves a net expense chargeable to the Institution's own funds of $47,031.09, resulting in net excess of income over expenses of $64,509.69.

The cash position was, however, not improved, due to the increase in accounts receivable from the Government as above stated. Practically our entire surplus of $137,000 was employed in financing Government contracts, as well as the balances due the Reserve Fund and Special Income Account above referred to, in addition to which it was necessary to borrow from the Bankers Trust Company from time to time on demand notes at 2% per annum. At the end of the year there was due the Bank on these loans the sum of $90,000. However, it is proposed by the Office of Scientific Research and Development that in the future we secure advances on account of the projects undertaken for that office, which in a short time should enable us to pay off all the loans and free our surplus.

The gross income on the securities in the Endowment Fund, excluding special income (extra dividends) was about 4.4% of cost and 4.47% of value at the end of the year.

The market value of the securities in the Endowment Fund at the end of the year was $18,724.09 under the cost, a situation which has considerably improved since that time.

1944

The accounts for the year 1944 have been audited by Messrs. Stagg, Mather & Hough, public accountants.

During the year bonds costing $170,943.75 were redeemed at a net profit of $10,886.24 (after adding applicable reserve for amortization).

During the year $179,018.60 was invested in bonds and $85,317.74 in stocks. The uninvested cash in the Endowment Fund at the end of the year was $10,573.67.

In addition to the amount of $29,880.76 due from the General Account to Special Income Account at the end of 1943 there was withheld during 1944 further special income of $3,238.75 plus an adjustment of $31.50 making a total of $33,151.01 due this fund at the year end. The continued withholding of these funds due Special Income Account was due to the financing of Government contracts.

The indebtedness of the Government at the end of the year 1944 had increased from $233,642.75 to an adjusted net of $293,754.62. Of this indebtedness more than $50,000 remains unpaid at the date of this report.

There was spent directly for the Government the sum of $805,502.89 in addition to which an adjusted overhead allowance calculated in accordance with the provisions of the contracts with the O.S.R.D. in the amount of $126,926.93 was agreed on.

Contracts "A" and "D" with the Bureau of Ships resulted in a direct loss in 1944 to the Institution of $17,859.19 and also in an indirect loss of $14,747.79 unrecoverable overhead.

The appropriation of $4,800 for the reserve for periodic replacements for 1944 as well as that for 1943 has not been transferred to that Reserve Fund. At the end of the year that Fund consisted of —

Bonds of the book value of	$48,262.50
(Market $48,408.70)	
Cash (including $9,600 due from General Fund)	10,437.64
	$58,700.14

The total income of the Institution from its Endowment Funds after the payment of custodian fees, was $111,331.24. This is $208.54 less than in 1943, and $293.39 more than in 1942. The total expenditures, excluding direct contract expenditures for the Government and including the loss on the Bureau of Ships contracts, amounted to $255,968.96. Reducing this by the sum of $126,926.93, the adjusted overhead allowance from the Government, leaves a net expenditure of $129,042.03 or $17,710.79 in excess of income. It is to be noted, however, that these expenditures include the investment in capital assets (purchase and improvement of Physalia and Little Reliance and additions to Library $27,808; and the unrecoverable direct expenditures on Contracts "A" and "D" $17,859.19).

Our cash position has not improved during the year. Our bank loans increased from $90,000 at the end of 1943 to $165,000 at the end of 1944. Our accounts payable from $15,474.52 to $71,033.68. Our entire surplus as well as the balances due the Reserve for Periodic Replacement Fund and Special Income Account were also used in financing the Government contracts. It was hoped to obviate this by securing advance payments but due to the O.S.R.D. rules banning advance payments on contracts within two months of termination and the fact that our contracts ran only for short periods, being constantly renewed, we received only two such payments.

The rate of return on the investments in the Endowment Fund, at cost, excluding Special Income, was 4.39%; including Special Income it was 4.51%.

At the end of the year 1943, the market value of the securities in the Endowment Fund was approximately $19,000 under the cost. At the end of 1944, this situation had markedly improved and there was an excess of market value over cost in all classes of securities. Our preferred stocks having an excess value of $69,069.93, our common stocks $34,464.42, and our bonds $61,501.93 over amortized cost.

1945

The accounts for the year 1945 have been audited by Messrs. Seamans, Stetson and Tuttle, C.P.A. of Boston.

During the year bonds costing $392,028 were redeemed at a net profit of $21,859.90. To this must be added $3,054.73, the applicable reserve for amortization, and an additional profit of $10,402.02 derived from the sale and redemption of stock, making a total net profit of $35,316.65.

During the year $241,811.62 was invested in bonds and $150,532.65 in stocks, leaving $108,868.58 uninvested at the end of the year.

The amount due from General Account to Special Income Account rose during the year from $33,151.01 to $37,094.76. The continued withholding of these funds due Special Income Account is a result of the financing of Government contracts.

The indebtedness of the Government rose during the year from $292,691.50 ($293,754.62 plus $4,352.68 billed after December 31, 1944, less $5,415.80 in overhead) to $468,991.71 not including unrecovered overhead of $34,129.70.

There was spent directly for the Government $859,188.06 in addition to which there was spent for General Overhead $159,222.11 and for Overhead on boats $112,978.74. Of these amounts $35,555.52 had not been recovered at the end of the year, but $29,725.68 was carried forward as recoverable in 1946. The remaining balance of $5,829.84 was accounted for by a charge to Institution expenditures of $1,372.64 representing the Institution's share of costs of work done under Contract A, and a charge of $4,457.20 to Government Allowances received for costs not otherwise provided for in the contracts.

The appropriations of $4,800 for the Reserve for Periodic Replacements for 1943, 1944 and 1945 have not been transferred to the Depreciation Fund. This fund consists of bonds of the book value of $40,200 (market $41,643.75) and cash (including $14,400 due from current funds) of $24,548.26, or a total of $64,748.26.

The total income of the Institution from its Endowment Fund after the payment of custodian fees was $116,969.34. This is over $5,000 more than in 1944. The net Institutional expenses amounted to $73,784.54 leaving a balance of $43,184.80.

Our cash position has not improved during the year. Our bank loans increased from $165,000 at the end of 1944 to $360,000 at the end of 1945. Our accounts payable decreased from $71,033.68 to $53,310.80.

Our entire surplus as well as the balances due the Reserve for Replacements and Special Income Account as well as the proceeds of the bank loans are involved in the financing of the Government contracts. It is hoped that this condition will improve during the year.

The return on the investments held at the end of the year excluding stock dividends was at the rate of a trifle over 4% on their cost.

At the end of the year the securities in the Endowment Fund were worth $2,844,919.11 which is $430,709.40 in excess of their cost.

Balance sheets and statements of income and expenses for the years 1943, 1944 and 1945 are appended, also the statement of income and expenses for 1942.

Respectfully submitted,

LAWRASON RIGGS
Treasurer

WOODS HOLE OCEANOGRAPHIC INSTITUTION — BALANCE SHEET

ASSETS

	Quoted Market Value	December 31, 1945		December 31, 1944		December 31, 1943	
ENDOWMENT FUND ASSETS							
Endowment Fund Assets:							
Bonds (less Reserve for Amortization of Bond Premiums. Note A)	$1,039,996.24	$974,803.09		$1,122,456.82		$1,113,099.43	
Stocks	$1,804,922.87	1,439,406.62		1,354,731.15		1,269,413.41	
Cash		108,868.58	$2,523,078.29	10,573.67	$2,487,761.64	94,362.56	$2,476,875.40
Reserve Fund Assets:							
Bonds	$10,150.00	$9,800.00		12,777.50		4,737.50	
Stocks	$16,346.75	19,099.02		19,099.02		19,099.02	
Cash		4,512.59	33,411.61	319.32	32,195.84	7,656.63	31,493.15
			$2,556,489.90		$2,519,957.48		$2,508,368.55
PLANT ASSETS							
Laboratory Plant:							
Land		$27,072.32		27,072.32		$27,072.32	
Buildings		332,202.26		323,063.12		323,213.12	
Laboratory Equipment		21,361.93		21,361.93		21,361.93	
Library		15,900.00		15,100.00		14,300.00	
Crew Room Equipment		—	$396,536.51	557.95	$387,155.32	557.95	$386,505.32
Ketch "Atlantis"							
Construction		$218,674.47		$218,674.47		$218,674.47	
Equipment		27,298.50	245,972.97	27,298.50	245,972.97	27,298.50	245,972.97
Ketch "Physalia"			23,408.00		23,658.00		—
Power Boat "Anton Dohrn"			17,145.67		17,145.67		17,145.67
Small Boats and Equipment			13,528.85		10,070.55		6,570.55
			$696,592.00		$684,002.51		656,194.51
Depreciation Fund Assets (for periodic replacements)							
Bonds (Quoted Market Value, 12/31/45, $41,643.75)		$40,200.00		48,262.50		17,195.00	
Cash (Note B)		24,548.26	64,748.26	10,437.64	58,700.14	36,263.18	53,458.18
			761,340.26		$742,702.65		$709,652.69

CURRENT ASSETS									
Current Funds Cash		$47,419.19			$27,124.36			$14,794.91	
Less: Amount due Special Income Fund	$37,094.76			$33,151.01			$29,880.76		
Amount due Depreciation Fund	14,400.00	51,494.76	($4,075.57)	9,600.00	42,751.01	($15,626.65)	4,800.00	34,680.76	($19,885.85)
Special Income Fund Assets									
Bonds (Quoted Market Value, 12/31/45, $8,500.00)		$8,500.00			$8,300.00			$8,100.00	
Stocks (Quoted Market Value, 12/31/45, $5,761.00)		4,345.66			3,513.77			2,872.21	
Cash (Note B)		38,190.40	51,036.06		34,042.98	45,856.75		30,616.98	41,589.19
Accounts Receivable									
United States Government Contracts									
Invoiced at December 31	$239,922.53			$92,246.37			$167,120.01		
Invoiced after December 31	229,069.18			200,445.13			67,802.53		
Unrecovered Overhead	34,129.70	$503,121.41		5,415.80	$298,107.30		(15,838.82)	$219,083.72	
Insurance Claims		1,105.00			18,189.85				
Advances to Scientists		6,679.64			5,444.23			1,311.97	
Sundry		1,663.13	512,569.18		415.68	322,157.06		1,325.68	221,721.37
Supplies in Stock			12,874.87			3,885.92			
Deferred Charge to Government Allowances			4,330.46						
			$576,735.00			$356,273.08			$243,424.71
Total Assets			$3,894,565.16			$3,618,933.21			$3,461,445.95
NOTES: Amounts shown in parentheses indicate negative figures.									
A Applicable Reserve for Amortization of Bond Premiums deducted from Endowment Fund Bonds		$2,557.88			$5,120.53			$6,403.07	
B Includes amounts due from Current Funds Cash as indicated under latter account.									

WOODS HOLE OCEANOGRAPHIC INSTITUTION — BALANCE SHEET (*Continued*)

FUNDS, LIABILITIES AND SURPLUS

	December 31, 1945			*December 31, 1944*			*December 31, 1943*		
ENDOWMENT FUNDS									
Endowment Fund—General		$2,000,000.00			$2,000,000.00			$2,000,000.00	
Endowment Fund—For Upkeep of Plant		419,419.96			419,419.96			419,419.96	
		$2,419,419.96			$2,419,419.96			$2,419,419.96	
Add Accumulated Net Gain on Securities Called or Sold		103,658.33	$2,523,078.29		68,341.68	$2,487,761.64		57,455.44	$2,476,875.40
Reserve Fund		$23,658.07			$23,395.57			$23,395.57	
Add Accumulated Reserve Fund Income		9,753.54	33,411.61		8,800.27	32,195.84		8,097.58	31,493.15
			$2,556,489.90			$2,519,957.48			$2,508,368.55
PLANT FUNDS									
Plant Fund—General		$607,642.13			$607,642.13			$607,642.13	
Plant Fund Reserve—Transferred in Prior Years from Current Surplus	$76,360.38			$48,552.38			$47,752.38		
Add Appropriations from Current Funds:									
Library Additions	800.00			800.00			800.00		
Administration Building	9,139.14			—			—		
Boat "Mytilus" (Note C)	3,458.30			—			—		
Ketch "Physalia"	—			23,658.00			—		
Boat "Little Reliance"	—			3,500.00			—		
	$89,757.82			$76,510.38			$48,552.38		
Deduct:									
Sale of Equipment	$250.00			$150.00			—		
Crew Room Equipment	557.95			—			—		
	$807.95	88,949.87	$696,592.00	$150.00	76,360.38	$684,002.51	—	48,552.38	$656,194.51
Reserve for Periodic Replacements			64,748.26			58,700.14			53,458.18
			$761,340.26			$742,702.65			$709,652.69
CURRENT LIABILTIES AND SURPLUS									
Accounts Payable			$53,310.80			$71,033.68			$15,474.52
Notes Payable—Bankers Trust Company			360,000.00			165,000.00			90,000.00
Surplus									
Balance at December 31, previous year	$120,239.40			$137,950.19			$73,440.50		
Add Excess of Income over Expenditures for the current year	43,184.80			(17,710.79)			64,509.69		
Balance at December 31, current year			163,424.20			120,239.40			137,950.19
			576,735.00			$356,273.08			$243,424.71
Total Funds, Current Liabilities, and Surplus			$3,894,565.16			$3,618,933.21			$3,461,445.95

NOTES: Amount shown in parentheses indicates negative figure.
C. Boat "Mytilus" acquired in 1943 and charged to Operations that year.

Income from Endowment Funds and Special Income Fund and Expenditures Applicable thereto
For the Years Ended December 31, 1945 and December 31, 1944

	Year Ended December 31, 1945			*Year Ended December 31, 1944*		
Income						
From Endowment Funds:						
Interest	$45,619.15			$47,722.88		
Dividends	72,600.40			64,828.33		
From Special Income Funds	435.01	$118,654.56		393.31	$112,944.52	
Less Custodian Fees and Expense		1,685.22			1,613.28	
Total Income			$116,969.34			$111,331.24
Institution Expenses						
Upkeep of Plant:						
Buildings and Grounds	2,739.73			6,525.44		
"Atlantis"	16,124.79			7,961.35		
"Asterias"	—			1,325.00		
"Anton Dohrn"	—			2,004.16		
Insurance (Note D)	—			4,270.87		
Depreciation	4,800.00	23,664.52		4,800.00	26,886.82	
Operating Expenses:						
"Atlantis"	3,556.47			21,036.89		
Scientific Salaries	18,111.13			5,354.14		
Scientific Supplies and Equipment	3,788.29			2,999.34		
Administration	1,755.71			712.35		
Traveling Expenses	1,628.97			596.89		
Contribution to Retirement Fund	1,603.73			1,587.49		
Amortization of Bond Premiums	492.08			722.45		
Publications	176.75			619.92		
Library (Note D)	—			1,100.00		
Bachelor Officers' Quarters (Net)	—	31,113.13		(311.73)	34,417.74	
Other Expenses						
Excess of Expenditures:						
Contract A	1,372.64			5,573.32		
Contract D	—			12,285.87		
Overhead:						
Current Year (Note E)	7,945.11			14,747.79		
Years, 1940, 1941 and 1942 (Note F)	—	9,317.75		7,322.49	39,929.47	
Expenditures for Permanent Plant Additions						
New Building	9,139.14			—		
Additions to Library	800.00			800.00		
Purchase Price and Cost of Installing New Motor-Ketch "Physalia"	—			23,658.00		
Purchase Price—Boat "Little Reliance"	—			3,500.00		
	9,939.14			27,958.00		
Less Amounts Received for Sale of Equipment	250.00	9,689.14		150.00	27,808.00	
Total Expenditures			73,784.54			129,042.03
Excess of Income over Expenditures			$43,184.80			—
Excess of Expenditures over Income			—			$17,710.79

NOTES: Amount shown in parentheses indicates negative figure.

D. Insurance and Library charges included in Overhead in 1945; made directly to Institution Expenses in 1944.

E. Overhead in 1945 apportioned to Institution Expenses on basis of ratio of Institution salaries to total salaries, including Government work. 1944 amount determined by different method which had the effect of apportionment but also includes Overhead loss on fixed-price Government contracts.

F. Overhead item for 1940, 1941 and 1942 represents amount deemed to be excessive recoveries from Government in those years and charged accordingly in 1944.

Statement of Income from Endowment Fund Investments and from Current Assets, and Expenses Applicable thereto, including Expenditures for Permanent Plant Additions (Less Allowance for General Overhead by the United States Government) for the Years Ended December 31, 1943 and December 31, 1942

	Year Ended December 31, 1943			*Year Ended December 31, 1942*		
Income:						
From Endowment Funds:						
Interest	$52,594.35			$51,777.88		
Dividends	60,534.81			60,849.84		
Net profit on preferred stocks called during the year, Special income	16.50			—		
		$113,145.66			$112,627.72	
Less—Custodian fees and expenses		1,604.88			1,589.87	
Expenses:			$111,540.78			$111,037.85
Upkeep of Plant:						
Upkeep of buildings and grounds	$11,608.22			$17,365.22		
Upkeep of "Atlantis"	469.87			9,393.41		
Upkeep of "Asterias"	134.23			611.34		
Upkeep of "Anton Dohrn"	4,858.53			3,369.28		
Insurance	6,045.77			7,129.83		
Depreciation	4,800.00			4,800.00		
Operating Expenses:		$27,916.62			$42,669.08	
Operation of "Atlantis"	10,888.85			$26,263.45		
Operation of "Anton Dohrn"	4,026.68			4,547.94		
Operation of "Asterias"	—			891.75		
Operation of "Mytilus"	4,597.81			—		
Operation of "Reliance", "Little Reliance" and other boats	7,963.35			—		
Scientists' salaries	19,576.63			23,218.70		
Scientific supplies and equipment	1,012.85			3,584.28		
Traveling expenses	1,386.15			881.28		
Publications	980.13			1,846.37		
Administration	31,247.71			14,171.23		
Amortization of bond premiums	1,008.74			1,288.63		
Contribution to retirement fund	1,382.64			1,382.83		
Interest on bank loans	414.73			152.22		
Mess (net)	2,851.05			785.93		
Housing (net)	5,316.59			—		
Library	1,050.00			—		
Station-wagon	205.47			—		
		$93,909.38			$79,014.61	
Total expenses		$121,826.00			$121,683.69	
Loss or gain on U. S. Government contracts (net):						
Loss on Contract A (less profit of $1,584.72 applicable to 1942)	9,830.37			—		
Less—Gain on Project No. 10	2,624.61	7,205.76		—		
		129,031.76			121,683.69	
Expenditures for permanent plant additions:						
Additions to library		800.00			800.00	
		129,831.76			122,483.69	
Deduct:						
Allowance for gen. overhead, by U. S. Government	98,639.49			$40,562.96		
Less—Excess charges on account of overhead on Government OSRD Contracts (B and C)	15,838.82	82,800.67	47,031.09	—	40,562.96	$81,920.73
Excess of income over expenses			$64,509.69			$29,117.12

IV. REPORT OF THE DIRECTOR FOR THE YEARS 1943, 1944, AND 1945

BY C. O'D. ISELIN

Introduction

The last published Annual Report of the Woods Hole Oceanographic Institution was for the year 1942. This indicated that the volume of work being carried out under government contract was increasing rapidly and that many of the members of our staff had dropped their normal studies. As the war progressed the number of unclassified projects being continued sank to a very low level and thus during the past three years there has been little that could be published concerning our activities. Furthermore, the publication of the Treasurer's report for the years after 1942 would have revealed the magnitude, if not the nature, of the investigations being undertaken at the request of the government.

Now that the war is over and the security regulations have been relaxed, it has become possible to present a general picture of the part played by this laboratory in the war effort. It should be emphasized at the outset that we at Woods Hole were by no means the only group in this country working on the military applications of oceanography, nor should we be given credit for more than a minor share of the successes. First under the leadership of the National Defense Research Committee and more recently under the direction of the Bureau of Ships and the Hydrographic Office all laboratories concerned with problems involving the sea have worked in closest collaboration. Each group conducted investigations for which their facilities and experience were best adapted, in most cases only part of a given project being carried out at any one laboratory. This "production line" system was on the whole very effective, the final assembly usually taking place within the Navy. In this way the limitations of a civilian organization in war time were largely overcome.

The history of our war time research program properly begins with the "Atlantis" observations of February 1937 off Guantanamo, Cuba. Using closely spaced mercurial thermometers, diurnal warming and its effect on sound transmission were studied in collaboration with the U.S.S. "Semmes". These preliminary observations, which were amplified during the following August, opened our eyes to the fact that physical oceanography plays a significant role in subsurface warfare. The only immediate effect, however, was to stimulate the development of the bathythermograph, an instrument much better adapted to the measurement of shallow thermal gradients than the conventional reversing thermometers.

In 1939 our second contact with naval applications of oceanography became established when Dr. Selman A. Waksman was asked to direct an investigation of the role of the slime film which forms on antifouling paints. Before two years had passed we found ourselves deep in the many interesting aspects of fouling, especially the fouling of more or less toxic surfaces. This investigation has in fact continued, under contract with the Bureau of Ships, right up to the present. However, we hope to complete our final reports during 1946.

It was not until the late summer of 1940 that we were asked to undertake a serious study of the role of oceanography in subsurface warfare. Although the possibilities could only be dimly foreseen, the National Defense Research Committee did not hesitate to back this research with all necessary funds. Thus almost overnight the number of qualified physical oceanographers in the country became entirely inadequate to deal with the several practical applications of their subject to modern warfare at sea. From that time on the personnel problem has been our chief one. The mistake that was made was that we did not at the outset undertake a teaching program. When the war began in earnest in December 1941 it was too late to organize such a program.

Increase in Staff

During the summer of 1940, the last normal year, there were about 60 people working in the laboratory. Although in science manpower is a poor measure of productivity, it may be of interest to list the total number of people employed here on August 31 during the past 6 years:

1941	107
1942	96
1943	173
1944	262
1945	335

Only part of this increase can be attributed to oceanography, for beginning in 1942 we turned over the top floor of the laboratory to a group working on explosives problems for the National Defense Research Committee. This group, which also grew very rapidly, became known as the Underwater Explosives Research Laboratory, Woods Hole Oceanographic Institution. Since September 1945 this project has been financed by a direct contract between the Bureau of Ordnance of the Navy Department and the Institution. Gradually the explosives research has become amalgamated with the more strictly oceanographic investigations. As time went on it became evident that the physics of an underwater explosion could not very well be kept separated from the physics of the environment. In fact, as will be explained more fully below, explosives have become an important tool in physical oceanography, in much the same way as in geophysics.

Returning to the figures listed above, even if only about half of the increase in staff during recent years was due to investigations more strictly oceanographic than explosions, how was it possible to find any such number of investigators with training in oceanographic research? The answer is that for the most part during the war period we have not been engaged in oceanographic research, but in the practical applications of physical oceanography. Thus geophysicists, geologists, meteorologists and biologists, to mention only a few of the types of investigators, all found a way to contribute to the work at hand. However, the stimulation to oceanography has been very considerable. Many investigators in allied fields have become genuinely interested in the ocean. Improvements in instrumentation have resulted in a large mass of new observations which have been studied, both from the practical point of view and from the standpoint of pure oceanography. Thus a number of important scientific advances have been made, but not nearly in proportion to the increase in our staff.

Since in general these results have not yet been worked up in a form suitable for publication in the oceanographic journals, one of the objectives of the present report is to present a summary of the investigations made by our war time staff. The individuals chiefly responsible will be mentioned under each subheading.

Increase in Laboratory and Shop Facilities

Such a large increase in staff would have been out of the question if only laboratory work had been involved for there are but 35 rooms in our main building. We have had recurring crises, but for the most part the field work has kept a considerable percentage of the staff away from Woods Hole. Also during the winter months we have been able to use space at the Marine Biological Laboratory as needed. Thus it has been the housing problem in the town, rather than laboratory facilities that has been the chief limitation.

The first major improvement to the main laboratory building was to equip a small machine shop in the basement. After about a year a larger shop was required and the former "Atlantis" crew room was fitted up as an instrument shop, the other room being reserved for general work with less precise tools.

Beginning in 1943 we acquired the use of the former Penzance Garage property next door. This permitted welding, brazing, pipe cutting, blacksmith work and tinsmith work to be taken out of the main building. It also provided ample storage space for government furnished equipment, lumber and other heavy supplies. The stock room, and an office for shipping and receiving were established in the former garage building. There remained some space for repairing boats, engines and automobiles. At the same time of course the wharf facilities were increased and the problem of parking cars was solved. It is difficult to see how we will ever manage to give up the use of this property which about doubles the useable space outdoors and more than doubles storage and workshop facilities.

Until about a year ago the administrative staff remained in the main laboratory building, in the end occupying four precious laboratories. Now all of the administrative personnel are housed in a temporary, two-story, wooden building, erected in the back yard in the former parking space. A smaller temporary building, which is used as an electrical laboratory, has been placed near the wharf, parallel to the pump house.

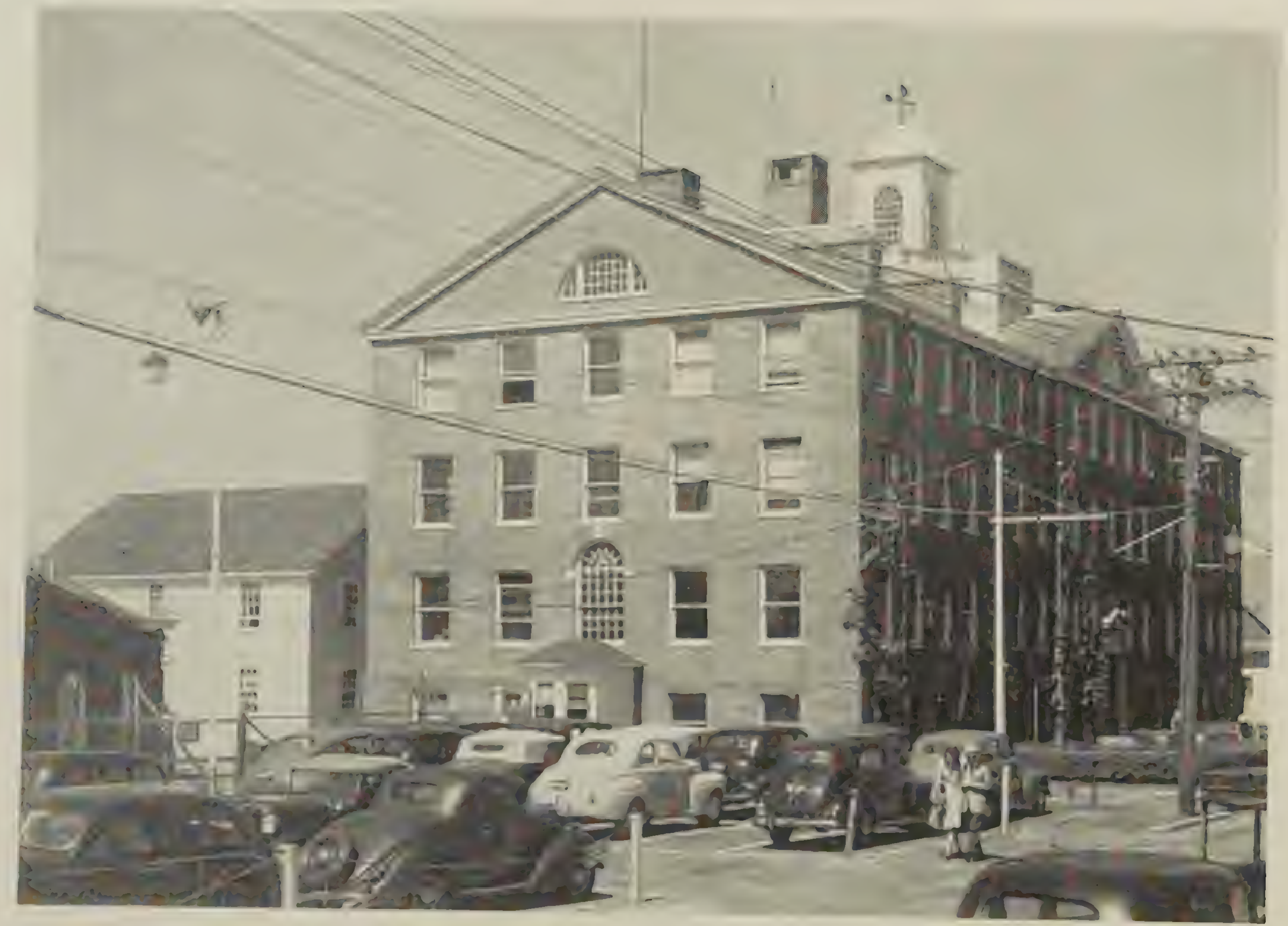
Meanwhile of course, the service departments such as drafting, duplicating, and photography had grown. When possible such work has been moved to the Marine Biological Laboratory, although both of our own dark rooms are still in routine use.

In many of the larger laboratory rooms temporary partitions have been erected in order to subdivide the space. In other cases many more people have managed to work in a given room than had ever been thought practical. Frequent reassignment of space has been necessary as the emphasis of the work shifted. Thus one way or another we have managed to provide more or less adequate laboratory facilities for the many different projects that have been undertaken during the war period.

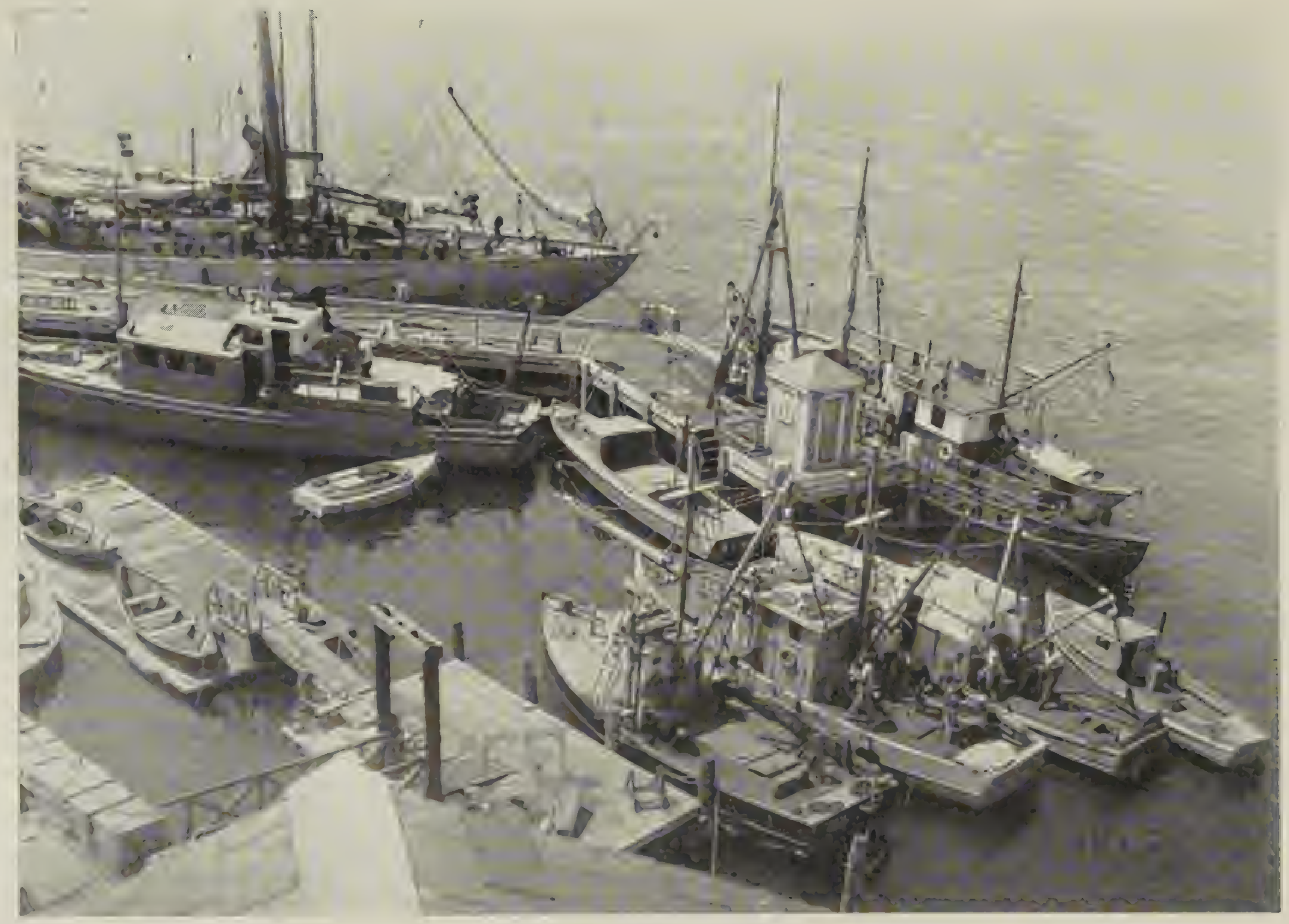
Boats

While we could not easily enlarge the laboratory, we had no trouble expanding our floating facilities. At one time as many as twelve assorted craft were being operated. Not all of these were actually owned by the Institution. From time to time Navy vessels have been assigned here for duty and some of the boats have been bought with contract funds. However, the Institution's own fleet has been expanded considerably.

With "Atlantis" and "Asterias" as a nucleus, the "Anton Dohrn", a gift from the Carnegie Corporation, was modernized in 1942. Next we bought "Mytilus", a relatively fast launch. She was followed in 1944 by "Physalia", a 64-foot motor-sailer of modern design and finally in 1945



View of the Laboratory from Main Street Showing the Parking Lot in Front of the Former Penzance Garage and the New Administration Building



The Northern End of the Wharf and Part of the Fleet of Boats Used During the Summer of 1945

we purchased "Reliance" which is almost a duplicate of "Asterias". The characteristics of these assorted craft can be listed as follows:

	Length in feet	Displacement in tons	Engine Horsepower
"Atlantis"	142	420	250
"Asterias"	40	8	40
"Anton Dohrn" . .	66	45	100
"Mytilus"	41	7	110
"Reliance"	38	7	35
"Physalia"	64	42	170

When the government financed vessels are added, it is evident that we must have a very considerable repair and maintenance problem on our hands. Mr. John Churchill has had this responsibility among several other major ones and he has organized an efficient repair crew of ship carpenters, electricians and mechanics. As time permitted, improvements have been made in all of the boats, both structural and mechanical. Especially, the electrical power supply and other facilities essential to the scientific work have been augmented.

With the exception of "Atlantis" it is of course a coastwise fleet. Since the first years of her reconversion we have seldom sent the "Anton Dohrn" more than a day's run offshore. Except in summer the "Physalia" too has been similarly restricted. Yet up to the present they have served their purposes very well indeed. We are lucky at Woods Hole to have sheltered and relatively deep waters so near at hand. It is seldom that within a day's sail of Woods Hole conditions cannot be found suitable for a given experiment.

The operation of "Atlantis" since she was laid up at Lake Charles, Louisiana, early in the war can be summarized as follows:

Cruise No.	Date	Region
129	Apr. 23–July 4, 1945	Woods Hole, Nassau and Bermuda
130	Aug. 8–11, 1945	Continental shelf, south of Block Island
131	Aug. 18–Sept. 12, 1945	Southeast of Bermuda
132	Oct. 11–16, 1945	Continental shelf, south of Block Island
133	Oct. 19–27, 1945	Slope water area, south of Martha's Vineyard
134	Nov. 13–21, 1945	Slope water area, southeast of Nantucket
135	Dec. 3–4, 1945	Continental shelf, south of Martha's Vineyard
136	Dec. 7–9, 1945	Continental shelf, south of Martha's Vineyard
137	Dec. 12–19, 1945	Block Island southward to Gulf Stream

Library

We have continued to set aside annually $800 toward the purchase of oceanographic books, journals, etc., for the library of the Marine Biological

Laboratory. There is now a considerable unexpended balance which has been set aside for the time when it will again be possible to resume buying in Europe. In addition, we have been making substantial annual contributions toward the administrative expenses of the library.

Publications

The following contributions were published during 1943, 1944 and 1945:

No. 252 R. B. Montgomery. Generalization for Cylinders of Prandtl's Linear Assumption for Mixing Length. *Annals N. Y. Acad. Sci.*, Vol. VLIV, Art. 1, pp. 89–103. 1943.

No. 293. Niels Haugaard and Laurence Irving. The Influence of Temperature upon the Oxygen Consumption of the Cunner (*Tautogolabrus adspersus* Walbaum) in Summer and in Winter. Journ. Cellular and Comp. Physiol., Vol. 21, No. 1, pp. 19–26. 1943.

No. 298. P. F. Scholander, Niels Haugaard and Laurence Irving. A Volumetric Respirometer for Aquatic Animals. *Review of Sci. Instruments*, Vol. 14, No. 2, pp. 48–51. 1943.

No. 302. G. A. Edwards and Laurence Irving. The Influence of Temperature and Season upon the Oxygen Consumption of the Sand Crab, *Emerita talpoida* Say. *Journ. Cellular and Comp. Physiol.*, Vol. 21, No. 2, pp. 169–182. 1943.

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Personnel

During the war years a total of 63 employees left the laboratory for active duty with the armed forces.

As discussed in an earlier section of this report, the number of workers has greatly increased since the last published Annual Report. These workers, primarily engaged on government contracts from 1942 to the present time, are listed below as of December 31, 1945. For completeness, all those whose term of service exceeds six months are included. A single year following a name indicates the entire period of service to be within that calendar year, two years denotes the beginning and end of employment, and one year followed by a dash indicates the year of employment and that he was still with the Institution at the end of the year 1945.

Scientists

Rolf F. Arentzen	1943–1945	Peter G. Bergmann	1945–
Arnold B. Arons	1943–	Stanley Bergstrom	1945–
Melvin Arsove	1944–	William C. Bohn	1945–
Thomas S. Austin	1944–	Richard M. Brown	1944–
John C. Ayers	1944–	William S. Butcher	1941–
David Barnes	1943–	Henry R. Cattley	1945–

Robert H. Cole	1942–
J. Stacey Coles	1943–
Robert D. Cotell	1945–
Wesley E. Curtis	1944–
John C. Decius	1944–
Edward S. Deevey, Jr.	1943–
W. T. Edmondson	1943–
John E. Eldridge	1943–1945
Gardner Emmons	1944–
David B. Ericson	1945–
John D. Ferry	1941–1945
William L. Ford	1944–
George Fraenkel	1943–
Frederick Fuglister	1941–
Paul M. Fye	1942–
Gabriel Gever	1945–
Richard Geyer	1944–1945
William E. Gordon	1943–
Robert W. Griffin	1945–
Edward J. Groth	1945–
Raymond R. Halverson	1944–1945
D. F. Hornig	1943–1944
J. L. Hough	1943–1945
Otis E. Hunt	1945–
Donald B. Johnstone	1942–1943
George Kahler	1945–
William D. Kennedy	1943–
D. E. Kirkpatrick	1942–1945
Marvin S. Klapper	1945–
Arthur A. Klebba	1944–
Victor Kumin	1943–1944
Emil Lehmann	1943–1944
Leonard N. Liebermann	1944–
Nelson Marshall	1943–1944
Kenneth McCasland	1945–
R. J. McCurdy, III	1940–
Sterling McNees	1945–
Frank J. Mather, III	1945–
Milton Miller	1943–
Emmeline Moore	1944–1945
Irvin M. Newell	1945–
Philip Newmark	1942–
Charles Niffenegger	1944–
Palmer Osborn	1943–1944
Ernest Patterson	1942–1945
Roger Patterson	1945–
James A. Peoples	1945–
Frederick deW. Pingree	1943–
Martin J. Pollak	1940–1944
Charles M. Pomerat	1942–1943
Robert S. Price	1943–
Donald M. Reynolds	1941–1944
Kenneth Reynolds	1943–1944
Harry H. Robinson	1944–1945
Henry Russell	1943–1944
Marshall Schalk	1943–
William Schevill	1943–
William G. Schneider	1943–
George T. Scott	1941–1944
Philip S. Shafer	1945–
Abraham M. Shanes	1942–1944
Nathaniel Shear	1945–
R. F. Shropshire	1943–1944
William S. Shultz	1943–
Charles P. Slichter	1943–
John P. Slifko	1942–
Eastman Smith	1944–1945
F. G. Walton Smith	1943–1945
Aaron Spector	1945–
Ralph W. Spitzer	1943–1945
David S. Stacey	1942–1945
Nelson Steenland	1944–
Henry M. Stommel	1944–
Elijah Swift, Jr.	1945–
Charles W. Tait	1944–1945
Herman A. Templin	1944–
Edward M. Thorndike	1942–1943
David Todd	1943–1945
Harry J. Turner	1944–
Adelaide Vine	1942–
Allyn C. Vine	1940–
William S. Von Arx	1945–
Charles M. Weiss	1939–
George N. White, Jr.	1945–
Rupert Wildt	1945–
Donald A. Wilson	1944–
E. Bright Wilson	1943–1944
William W. Wood	1943–1945
George Woollard	1942–
J. L. Worzel	1940–
Arthur J. Yaspan	1945–
Thomas Zandstra	1943–1944
Donald J. Zinn	1945–

Technicians

John M. Aitchison	1945–
Jean Arentzen	1943–1945
Barbara Atwood	1945–
Catherine G. Ayers	1944–1945
L. H. Barbour	1943–
Thomas C. Bardwell	1945–
Beverly A. Berg	1942–1945
Ruth Billard	1945–
Charles F. Blevins	1944–
Barbara Brooks	1942–
Patricia Brown	1943–
Vertene Brown	1945–
Elizabeth T. Bunce	1944–
Margaret Burrows	1944–1945
W. Graham Campbell	1945–
Jeanne Carritt	1942–1943
Helene Chamberlain	1945–
Ermine A. Christian	1945–
Gloria S. Clark	1945–
Mary C. Cobb	1942–
Richard L. Cole	1943–1945
Elizabeth Copeland	1943–1944
Jeanne D. Conners	1944–1945
Barbara A. Cotter	1945–
Dorcas H. Crary	1941–1944
Dorothy Day	1944–
William E. Day	1945–
Raymond E. Deysher	1941–1944
Elizabeth S. Diaco	1945–
Kathryn M. Doane	1944–
Jean DuMont	1943–1944
Gerritt Duys, Jr.	1944–
Yvette Edmondson	1945–
Margaret K. Ewing	1942–
Barbara M. Ferry	1942–1944
Harold P. Field	1944–
Constance French	1943–
Nancy N. Friar	1945–
Bernice E. Grahn	1944–1945
Eunice S. Groh	1944–
Margaret F. Halverson	1944–1945
Gardner Handy	1942–1945
Barbara Hathaway	1944–
Marion W. Hawes	1945–
Kristi Hay	1944
Anne L. Hayer	1944–1945
Carlyle R. Hayes	1945–
Mary Hegarty	1945–
Eleanor Hern	1944–
Janet R. Jenkins	1944–1945
Janet Johnson	1945–
Richard L. Kaye	1944–1945
Dorothy Keen	1944–
Jean D. Kennedy	1943–1945
Priscilla Knott	1943–1945
Jean Lacey	1944–1945
Frederick B. Laidlaw	1943–1944
Helen S. Magee	1943–1945
Mary L. McClung	1943–1945
Sol W. Malaskey	1945–
John G. Mangan	1945–
John P. Manry	1944–1945
Virginia Maple	1943–
Mildred Melody	1943–1945
William Metcalf	1945–
Virginia Milanese	1943–1944
Robert B. Mills	1945–
Frances Moore	1943–1945
Elizabeth W. Olmsted	1944–1945
Elliott Orr	1943–1945
Zoe Ann Orr	1944–1945
Johnson Parker	1941–1944
Barbara Perkins	1945–
Hazel Pingree	1943–
Lynn D. Quick	1944–1945
Mary Anne Rogers	1945–
Francis C. Ronne	1944–
Dorothy Ryder	1943–
Eileen Scharff	1943–
Margaret Scharff	1944–
Jean Schneider	1943–1944
Ruth E. Senate	1945–
Deskin H. Shurbet	1942–1943
Vernon Smith	1943–1945
Anne E. Snipes	1945–
Oakes Spalding	1941–
Elizabeth Sparks	1945–
Beverly L. Steele	1944–1945
Edith Stokey	1943–1945
Pearl E. Struth	1945–
Doris T. Tassinari	1944–
Alice K. Taylor	1945–
Vivian Templin	1945–
Anne Thomas	1943

Wesley B. Thompson	1944–1945	Ruth L. Von Arx	1945–
George B. Tirey	1941–	Sylvia Weare	1944–
Evangeline Tollio	1944–	Fleeta Wilkie	1943–1944
Sonia Trabun	1945–	Frances Williams	1943–1944
Betsy A. Turner	1944–	Catherine Wingate	1945–
Mary Turner	1944–	Grace L. Winter	1945–
Virginia Vail	1944–	L. V. Worthington	1941–1943

Laboratory Assistants

Herbert Alberts	1942–	Doris M. Lumbert	1945–
Dorothy Allen	1943–1944	John R. Martin	1943–1945
Ruth W. Allen	1942–1943	Margaret W. Miller	1944–1945
Nellie Anderson	1943–	George Ostiguy	1945–
Jean Arons	1943–1944	Beth R. Perry	1943–1945
David Baldwin	1944–1945	Carol Peterson	1943–1945
Elizabeth P. Barber	1944	Janet Peterson	1945–
Abner Briggs	1943–1944	John M. Powers	1941–1945
Joan A. Brown	1944–	Lavenna Putman	1943–1944
Margaret Butler	1944–1945	Alfred G. Redfield	1942–
Elizabeth F. Cole	1941–	Martha Redfield	1942–1944
Georgiana Deevey	1945–	Beatrice Reynolds	1943–1944
Dorothy Donnelly	1944–	Albert J. Riehl	1944–
Robert W. Donnelly	1945–	Marilyn Rockwell	1945–
George P. Dutra	1945–	Solange Saulnier	1943–1944
Beverly Emery	1943–	George F. Savery	1942–1944
Alice Ferris	1943–	Harold Schweidenback	1945–
Axel Frank	1943–1945	Nancy Sisson	1943–
Carl A. Frank	1943–1945	Philip Spalding	1942–
Alex. C. Frue	1945–	Joan M. Spillane	1943–1944
Mary Gerbacia	1943–1944	Joan L. Stacey	1944–1945
Robert A. Goffin	1943–	Richard Stansfield	1942–
George A. Gordon	1945–	James R. Sullivan	1945–
Nancy Hamlen	1944–1945	Esther Tsiknas	1944–1945
Harold L. Handy	1944–1945	Iona Walker	1945–
Wilfred H. Huntington	1944–	Charles L. Wheeler	1943–
Helen S. Hutchins	1944–	Howard H. Williams	1942–1944
Roger Kuhn	1943–1945	Allen L. Windle	1945–
Anne E. Lawrence	1944–1945	Fred C. Woodward, Jr.	1945–

Administration

Norman T. Allen	1941–	Marcus Conlan	1942–
C. L. Barber	1943–1944	Marie G. Dever	1944–1945
Edwin T. Bryant	1945–	Mary Donald	1945–
Clinton Cahoon	1945–	T. S. Perry Griffin	1944–
Edith L. Cassick	1944–1945	Caroline M. Reiser	1945–
John Churchill	1942–	Ethelyn T. Slifko	1940–
Katherine Churchill	1943–1945	Ethel E. Wagner	1945–

Secretaries

Virginia P. Alberts	1943–
Jeanne Backus	1943–
Patricia Backus	1943–
Arshales Baker	1943–
Phyllis M. Behnke	1945–
Madeline Broadbent	1944–
Vivien Brown	1944–
Mary L. Campbell	1944–
Anne Castellini	1943
Charlotte G. Christian	1941–1945
Genevieve C. Doyle	1945–
Evelyn Fleming	1943–1944
Ruth E. Fye	1942–
Anita W. Gallagher	1945–
Willia Harlow	1945–
Marion L. Havener	1944–1945
Mary Howze	1943–1945
Romayne L. Jeffery	1944–1945
Norma A. Joseph	1945–
Blanche Klapper	1945–
Lucile V. Korf	1944–1945
Lucile A. Krause	1945–
Florence K. Mellor	1944–
Dorothy Onan	1943–1944
Betty P. Ostiguy	1945–
Anne Palmer	1943–
Helen M. Penney	1944–1945
Camille Piccolli	1945–
Calla Shelton	1945–
Edith H. Sparks	1945–
Troy Tapp	1943–1944
Evelyn M. Taylor	1944–1945
Lois M. Vaetsch	1945–
Charlotte Vail	1944–
Chessie M. Williams	1945–
Ruth A. Wirick	1944–

Maintenance and Shop Workers

Robert Adams	1943–
Clarence Anderson	1945–
John W. Barlow	1943–1945
Forrest W. Blake	1944–
R. H. Bodman	1942–
Warren E. Brightman	1943–
Milton F. Buckley	1943–1944
Carl N. Carlson	1944–
James S. Condinho	1945
Henry Churbuck	1942–1945
John William Condon	1932–
James Francis Diaco	1944–1945
Paul Dingwell	1943–1944
Edith Dorsett	1943–1945
Elwood Eldridge	1943–1945
Stanley Eldridge	1940–
Leola Erskine	1943–1944
Wayne J. Fisher	1944–1945
Fred Gaskell	1945–
Charles E. L. Gifford	1944–
Francis X. Glynn	1941–1944
Reuben Hamblin	1942–1943
Frank O. W. Handy	1942–
Harry H. Handy	1943–
Hiram C. F. Harlow	1944–1945
Seaver R. Harlow	1943–
Sterling W. Haverfield	1945–
Harry Hodgkins	1944–
Elijah Howes	1942–
William L. Howes	1943–
Robert Liljestrand	1942–1943
Benjamin Lintner	1945–
Henry Mandly, Jr.	1937–
Wallace R. Marrow	1945–
Carleton Mixer	1944–
David Molleur	1945–
Kenneth Morrison	1943–
Ellen A. Murphy	1945–
Esther Owen	1943–1945
Angelo S. Pacheco	1944–
Sidney F. Peck	1943–
Wm. L. Plamondon	1944–
Joseph Quinlan	1945–
Oliver W. Robinson	1944–
James Salthouse	1941–
George H. Savery	1943–1944
Nat Simmons	1945–
Ida Soderland	1943–
Otto Solberg	1944–
Lawrence A. Thayer	1944–

Catherine Turner	1944–	Hallet Wagstaff	1943–
Kenneth Turner	1943–1944	Carleton Wing	1940–
Thomas Turner	1943–1945	Nathaniel Wing	1942–

Boatmen

Edwin Athearn	1941–1944	Dana R. Lange	1940–1944
Harold Backus	1931–	Elliott Mayhew	1943–
Elmer Barstow	1943–	Herbert E. Mayhew	1943–1944
Lennert S. Blomberg	1944–	Paul Mayhew	1943–
Lloyd H. Bosworth	1944–1945	Albert Nickerson	1944–1945
Russell Bosworth	1944–	Alfred E. Norton	1944–
Hartley Cassidy	1943–1945	Gilbert Oakley, Jr.	1940–
Clarence F. Chase	1944–1945	Joseph A. Orr, Jr.	1944–1945
Hans Cook	1934–	William D. Payne	1944–
Benjamin Cromwell	1945–	Ray Peters	1945–
Herbert M. Davidson	1945–	Matthew F. Pells	1944–1945
Ernest Dean	1944–	Stanley E. Poole	1941–
Charles G. Dyer	1945–	Elmer L. Rogers	1944–
Donald Fay	1945–	C. Otto Schweidenback	1945–
Albert O. Fischer	1944–	Edward A. Shaffner	1943–1944
William F. Gallagher	1945–	Ernest Siversen	1935–
F. Lawrence Goodwin	1945–	Harry C. Studley	1944–1945
John P. Harlow	1944–1945	Ralph Tilton	1943–1944
Nils C. Iverson	1945–	Gordon W. Weeks	1944–1945
Arvid Karlson	1945–	Norman C. West	1943–
Leroy C. Lair	1943–	David L. Whittemore	1943–1945

Scientific Program

The following summary of the major investigations undertaken during the past three years will deal primarily with the scientific aspects of the various problems, rather than with their practical applications. As stated previously, throughout the war period the reverse emphasis prevailed. Thus the scientific advances may appear to be rather small, considering the size of the staffs involved.

1. Antifouling paints and fouling organisms.

A staff of about twenty persons under the general supervision of Dr. Alfred C. Redfield has been busy throughout the war period in studies designed to improve understanding of the performance of antifouling paints, and to increase knowledge concerning the distribution and rate of growth of the fouling organisms. Dr. Bostwick H. Ketchum and Dr. John Ferry have worked primarily on the physical chemistry of paint systems. Dr. Louis Hutchins and Dr. Edward Deevey have been concerned mainly with the biological aspects of fouling. Most of the work has been under contract with the Bureau of Ships (Research and Standards Section), but the Institution also contributed some funds for the biological studies.

On the technical side the main objective was to develop a quicker and more reliable method of testing the antifouling characteristics of paints. This involved, first of all, learning how the paints prevented fouling. It was found that the rate at which the toxic dissolved from a paint was the most important factor in determining its effectiveness. The copper leaches from some paints too rapidly and thus the antifouling properties are quickly lost. Other paints are so insoluble that the toxic remains locked up in the paint coating and does not poison the organisms which settle on its surface. It became possible to develop purely chemical methods of measuring the leaching rate of antifouling paints which can be carried out in the laboratory, and are independent of the availability of fouling organisms.

Once the importance of the rate of dissolution of the paint was demonstrated, the next obvious step was to examine the physical and chemical properties of the toxics, and organic matrix ingredients, and of the complete paint system so as to be able to control the process. These studies have led to new and definite ideas about the way in which paints behave during exposure to sea water, and about the way in which various components of paint determine its effective behavior. The design of paint is thus passing out of the cook book stage onto a more secure engineering basis. As a by-product, new information has been secured about the solubility reactions of copper compounds and of various resins with sea water.

In all this development an important factor has been the close cooperation which has been achieved between the Navy's paint laboratories and the group at Woods Hole.

In order that the chemical studies could be checked by exposing panels painted with the various experimental formulations, the Institution maintained a test station at Miami where fouling is severe throughout the year. Dr. C. M. Pomerat, Dr. F. G. Walton Smith, and Mr. Charles M. Weiss, who in turn supervised this work also found time to make many valuable studies of the fouling process and of the biology of the organisms involved. In addition the station was used to an increasing degree for testing paints and other materials for the various Navy paint laboratories. Extensive tests of the actual performance of antifouling paints in service were also conducted from the Miami station. This work was greatly facilitated by the cooperation of the University of Miami, which made space available in its Marine Laboratory and was helpful in many other ways.

The need for detailed information on the tendency for various naval installations to foul led to the collection of a large number of samples of the growth from navigation buoys and their mooring chains from all parts of the coast of the United States. The study of this material has already provided much new information on the depth and distance from shore at which fouling is to be expected, the relation of temperature to its rate of growth, and the geographical limits of the occurrence of the various species. The collections provide an uniquely comprehensive sampling of the sessile marine organisms of the sea coast. Their complete study should result in a very valuable contribution to biogeography.

Eight scientific papers have already been published, or are in press, in which the results of these chemical and biological by-products of the fouling studies are presented, and others should follow. In addition, at the present time a book is being written to be entitled "Marine Fouling and its Prevention". This will not only summarize the work carried on here during recent years for the Bureau of Ships, Navy Department, but it will also review critically the extensive scientific and technical literature on the subject. The chapters dealing with paint technology were distributed in preliminary form last September to the interested agencies and individuals for criticism. It is expected that the remainder will be completed and the book be ready for press by the end of the summer of 1946.

The completion of this book will mark a natural turning point in such studies. As an oceanographic laboratory we have carried the technological problems of the prevention of fouling to the point where they can be turned over to the paint laboratories with a clear understanding of the requirements imposed by biological considerations. On the other hand, it has become apparent that the fouling organisms themselves afford an opportunity which has not been adequately exploited for the study of many problems in the geographical distribution of marine organisms and the productivity of the sea. Studies of this sort could be profitably continued.

2. Temperature distribution in the surface layer of the North Atlantic.

Under this heading fall the studies which have become possible through the very great improvements in the bathythermograph which were achieved during 1941 and 1942. Starting with a relatively crude instrument, which could be used only at slow speeds, Dr. W. M. Ewing and Mr. Allyn C. Vine developed the basic idea behind Dr. A. F. Spilhaus' original design to the point where reliable temperature-depth curves down to roughly 150 meters could be secured from vessels traveling at speeds up to 20 knots. The applications of the bathythermograph to subsurface warfare are such that the Navy procured and put into routine services a considerable number of these instruments. At the present time from the North Atlantic alone some 60,000 records have accumulated.

This extensive file of new temperature data has been combined with the pre-war, published, subsurface temperature observations in such a way that studies of the seasonal and diurnal thermal cycle are greatly facilitated. Under the direction of Mr. Frederick Fuglister average monthly values of the temperature at various standard levels down to 200 meters have been tabulated for each 30 minute square in the North Atlantic. The data are of course unevenly distributed, both with time and in the geographical sense; however, by combining observations from somewhat larger areas it is possible to follow the seasonal changes in considerable detail. Especially in the triangular sector between Cape Hatteras, Bermuda and the Grand Banks the average monthly values are derived from observations made over a considerable number of years. Thus we are approaching the time when studies of the annual temperature variations over relatively large areas of the ocean might be undertaken.

Many of the bathythermograph records, especially from the western North Atlantic, are in the form of sections of closely spaced lowerings. These are very helpful in determining the location of the important oceanographic boundaries such as the edge of the Gulf Stream and the offshore limits of coastal water. They also show in very satisfactory detail the mixing processes which occur near the margins of the currents. At present it can be considered that because of bathythermograph observations oceanography in this respect is somewhat ahead of meteorology.

In some regions temperature data alone, however detailed, are difficult to interpret in the absence of corresponding salinity measurements. The ideal arrangement would be to measure both temperature and salinity as a function of depth and then automatically combine them to record density. Several promising advances have been made in this direction. Various types of conductivity cells have been designed and tested. Electrical circuits have been worked out so that salinity or density can be recorded on deck as the conductivity cell and a suitable thermal element are lowered into the sea at the end of an electrical cable. This type of instrument has been shown to be practical and useful for observations down to a depth of about 200 meters. The next step will be to build a self powered instrument to be lowered from a hydrographic winch so that much deeper soundings will be possible. Such an instrument is still in the design stage. Enough tests of the various component parts have been made so that we are quite confident that the desired accuracy can be gained. The instrument, if successful, will be analogous to a barometer in meteorology in that it will sum the density of the water column through which it is lowered and thus rather directly will permit the relative topography of the sea surface to be plotted. If closely spaced observations of this type can be made without too much delaying the ship, much more reliable studies of the dynamics of ocean currents can be carried out than has been possible with the conventional water-bottles and reversing thermometers.

3. Air turbulence and convection over the ocean.

These studies stemmed from Mr. Alfred Woodcock's interest in the curious correlations between specific flight routines of herring gulls and co-existing thermal and flow relationships between sea and air. He accumulated evidence that when the air is gaining heat from the sea some sort of patterned convective motions are set up. There was evidence that these motions were similar to small scale convection cells which have been studied in the laboratory.

His war time studies of air motions were first centered around the problem of predicting the performance of smoke screens over the water, and especially in gaining a better understanding of the relatively complicated thermal structure which may exist in the lower air near a beach. A simple mechanical air thermograph, to be raised by a kite or balloon, was developed which greatly facilitated measurements of vertical temperature gradients at low elevations. This instrument is more inconvenient in use than the bathythermograph which serves the corresponding purpose in the oceans. This is due primarily to the widely differing physical constants of sea to air and to the simple fact that the observing platform does not move with the medium measured, as does the ship. With the aid of the air thermograph and other standard instruments, analysis of smoke screen behavior could be placed upon a physical basis. These studies were useful in furthering an understanding of lower air motion and have led directly to methods for deriving a much more complete physical picture of the air-sea inter-relationships.

As the program expanded Dr. Jeffries Wyman took over general supervision of the group studying low level meteorological phenomenon over the ocean. Instruments were developed to record wet and dry bulb temperatures simultaneously in order to help determine the scale of the convective motions under various conditions of wind and air-water temperature difference. More recently a considerable variety of recording instruments, including sensitive accelerometers and a new type of psychrograph, have been specially adapted for use on a relatively slow aeroplane. This is in preparation for studies of the structure of the lower atmosphere in the course of long flights over the ocean. It is also expected that arrangements can be made for the plane to collaborate with a surface vessel in studies of the heat exchange between the two mediums. The development and testing of suitable instruments for this program was practically completed in 1945.

4. Sea, swell and surf.

The methods developed at the Scripps Institution of Oceanography for forecasting sea and swell, and the studies of surf carried out principally at the University of California emphasized the need for improved instruments to record sea and swell. Accordingly, early in the war we were asked to undertake such a development and at the same time to study the surf conditions along the Atlantic coast.

The early instrumental work was carried out under the supervision of Dr. W. M. Ewing. More recently Mr. Arthur Klebba has been in direct charge of the wave instrument program. Dr. George Clarke, assisted by Mr. Gardner Emmons and others, carried out measurements of the surf at a number of points along the coast and used these data to check several problems related to the forecasting methods.

Knowledge concerning waves advanced very rapidly during the war period and the results are being published by the Hydrographic Office. Wave theory, on the whole, outstripped the observational program, mainly because of the lack of suitable instruments. Recently, following a British development, Mr. Klebba has constructed a wave period analyzer which has great promise in the future of wave research. This instrument takes the record from his swell recorder and resolves the frequencies of the various wave trains making up the swell. An experimental wave recorder station is being set up at Cuttyhunk Island, about 14 miles west of Woods Hole, and it is expected that during 1946 another station will be installed at Bermuda where deep water wave characteristics can be conveniently recorded.

5. Underwater acoustics.

This subject is intimately bound up with physical oceanography and submarine geology. During the war years, under contracts administered by the National Defense Research Committee very great advances have been made. The contributions of the many investigators at the several laboratories engaged in this work will shortly be published. Since March 1944 the work in underwater acoustics at Woods Hole has been continued under contract with the Bureau of Ships (Underwater Sound Design Section).

From the oceanographic standpoint, perhaps the most interesting development in underwater acoustics is the system proposed by Dr. W. M. Ewing for locating survivors at sea. To date nearly all of the research in this connection has been carried out by members of our staff. The basic ideas involved have recently been made public by the Navy Department under the code name SOFAR.

Dr. Ewing realized that at mid-depths over large areas of the ocean there exists a layer where the speed of sound is at a minimum, forming a so-called sound channel. This layer is just below the main thermocline and thus varies slightly in depth geographically. Over most of the North Atlantic the minimum velocity layer is at a depth of about 1300 meters. Because of refraction effects, signals emitted in this layer can travel very long distances without having to undergo either bottom or surface reflection. Thus acoustical transmission in this layer is relatively efficient and a receiver located at similar depth can record signals originating several thousand miles away.

It is convenient to use a small bomb (one or two pounds of explosives) as the sound source. Mr. J. L. Worzel, who has taken an active part in this project, worked out the details of a very simple fuse to fire a bomb near the desired depth. The time differences in the arrival of this signal at three widely spaced receiving stations establishes a fix. At the present time the Navy is planning to set up an experimental operating system to monitor the flight routes in the eastern North Pacific.

In order to study the potentialities of this means of communication and location, in 1944 we established a receiving station on Eleuthera Island in the Bahamas. This station was in operation for nearly a year during which time signals were recorded from wide areas of the North Atlantic, the maximum range being 3200 miles. For the sound to reach the receiver it is necessary that no obstruction occur along the great circle track between the source and the receiving station. Thus it is possible to sweep acoustically large areas of the ocean and to locate any submerged mountain peaks which interrupt the permanent sound channel. Several probable shoal areas in the North Atlantic have already been located in this manner.

It is clear that if Sofar is to become at all widely used in Air-Sea Rescue, the study of the distribution of temperature and salinity at mid-depths, and the charting of submerged peaks will be greatly stimulated. The ultimate limitations of the system will be determined by these factors, rather than by the sensitivity of the receiving equipment.

The environment of course influences acoustical transmission in many other ways. Especially for the higher frequencies, the vertical thermal structure becomes important. For the lower frequencies in deep water and for the higher frequencies in shallow water the bottom sediments must often be taken into account. Short period internal waves and very small scale thermal structure have also received some attention because they too influence the transmission of sound. It is believed that sound has become an important auxiliary means of exploring the ocean and that acoustical studies will continue to be carried out in close association with oceanography.

Special mention should be made of the considerable number of sediment charts prepared during recent years under the direction of Mr. Henry C. Stetson. All available sedimentary data from the continental shelf along the Atlantic and Gulf coasts were reexamined by Mr. Stetson, and a complete set of sediment charts prepared for publication by the Hydrographic Office. He also undertook studies of the coastal sediments in many foreign areas, as required by the Hydrographic Office. The resulting charts have recently been released to the public.

While this was a rather specialized form of submarine geology, in that the sediments were classified under only six headings, nevertheless, it has led to a better general understanding of the distribution of the basic types of marine sediments and of the factors influencing this distribution.

6. Seismic Refraction Measurements in Shallow Water.

In 1944 as part of some studies undertaken for the Naval Ordnance Laboratory, Dr. W. M. Ewing and Mr. J. L. Worzel were able to work a number of seismic stations in Chesapeake Bay, off Jacksonville, near the Virgin Islands, off Barbados, off the Orinoco River and in the Gulf of Paria. Their instrumentation was superior to that previously used at sea and in each locality they obtained definite evidence as to the thickness of the unconsolidated sediments. The high quality of the records has served to clarify many problems of the transmission of sound waves both in the water and through the bottom. The results have been reported in preliminary form at a meeting of the Geological Society of America.

The many seismograms obtained in the course of the work provided excellent data for studies of the dispersion of the water wave, phenomena noted previously in which the higher frequency sound arrives ahead of the lower. Using the new data, Dr. C. L. Pekeris has recently completed a theoretical study which establishes a complete and detailed explanation of the observed dispersion in terms of bottom structure and the depth of the water. As the wave length of the sound approaches the depth of the water ray acoustics do not hold and wave acoustics must be used. The theory shows that a wave is developed which travels along the ocean floor and that measurement of the dispersion in the water wave may be used to determine the sound velocity in the ocean bottom to a depth approximately equal to the depth of the water. Although it has been used to date only in shallow water, the method is feasible for oceanic depths. During 1946 Dr. Ewing expects to resume field work in the application of geophysical methods to problems in submarine geology.

7. Underwater explosive phenomena.

As mentioned previously, during the war period a considerable proportion of our staff has been engaged in studying the physics of explosions, both in the air and in the water. In both media much of the work has centered around the problem of developing better gauges for measuring the pressure wave produced by an explosion. At first relatively small charges were sufficient for calibrating and evaluating the various types of gauges studied, but inevitably we found ourselves working with larger and larger amounts of explosive materials.

Permission was secured to establish magazines and a small chemical laboratory for making up special charges on Nonamesset Island, directly across Woods Hole Harbor from the main laboratory building. The schooner "Reliance" was bought with contract funds and gradually fitted out with all the necessary instrumentation for explosive experiments in Vineyard Sound. From time to time the "Atlantis" has been used for special experiments which could best be carried out at greater distances from Woods Hole. Various other smaller craft have also been employed in this work. However, since research on explosives, even when they are used in the sea, is only remotely connected with oceanography, no attempt will be made here to discuss the full scope of this particular part of our war time program, the results of which will before long become available through the Office of Scientific Research and Development.

At the outset the explosives investigations were directed by Dr. E. Bright Wilson, Jr. He was succeeded by Dr. Paul C. Cross when Dr. Wilson had to leave to become a Division Chairman of the National Defense Research Committee. Dr. Paul Fye, Dr. Robert H. Cole, and Dr. J. Stacy Coles have had the primary responsibility in the underwater work, while Dr. William Kennedy has been in direct charge of the air blast measurements. It is expected that this particular part of our program will be terminated during 1946.

It should perhaps be added that from the standpoint of oceanography this work has been of value because much experience has been gained in carrying out elaborate and precise experiments at sea. The use of complicated electronic instruments on shipboard is a relatively new problem, but in all probability it will be a continuing one in oceanography.

V. STAFF

(As of December 31, 1945)

Columbus O'D. Iselin, Associate Professor of Physical Oceanography, Harvard University, and Associate Curator of Oceanography, Museum of Comparative Zoölogy; Director.

Alfred C. Redfield, Professor of Physiology, Harvard University; Associate Director.

Clifford A. Barnes, Lieut. Comdr., U. S. Coast Guard Reserve; Associate in Physical Oceanography.

Dean F. Bumpus, Associate in Oceanography.

Cornelia L. Carey, Associate Professor of Botany, Barnard College; Associate in Marine Bacteriology.

George L. Clarke, Associate Professor of Zoölogy, Harvard University; Marine Biologist.

Paul C. Cross, Professor of Physical Chemistry, Brown University; Associate in Chemistry.

William Maurice Ewing, Associate Professor of Geology, Columbia University; Associate in Submarine Geology.

Louis W. Hutchins, Associate in Marine Biology.

Bostwick H. Ketchum, Associate in Marine Biology.

Raymond B. Montgomery, Physical Oceanographer.

Fred B. Phleger, Jr., Associate Professor of Geology, Amherst College; Associate in Submarine Geology.

Norris W. Rakestraw, Professor of Chemistry, Brown University; Chemical Oceanography.

Charles E. Renn, Associate Sanitary Biologist, Massachusetts Dept. of Public Health; Associate in Marine Bacteriology.

Gordon A. Riley, Research Associate, Bingham Oceanographic Foundation; Marine Physiologist.

C. G. Rossby, Professor of Meteorology, University of Chicago, and Assistant Chief, U.S. Weather Bureau, Washington, D. C.; Associate in Physical Oceanography.

Mary Sears, Lieut. Comdr., U. S. Naval Reserve (W); Planktonologist.

H. R. Seiwell, Lt. Col., Corps of Engineers, U. S. Army; Physical Oceanographer.

Floyd M. Soule, Comdr., U. S. Coast Guard Reserve; Associate in Physical Oceanography.

Athelstan F. Spilhaus, Major, Weather Division, U. S. Army Air Forces; Physical Oceanographer.

Henry C. Stetson, Associate Curator of Oceanography and Alexander Agassiz Fellow, Museum of Comparative Zoölogy; Submarine Geologist.

Selman A. Waksman, Professor of Microbiology, New Jersey Agricultural Experiment Station; Marine Bacteriologist.

Edmond E. Watson, Associate Professor of Physics, Queen's University; Physical Oceanographer.

Alfred H. Woodcock, Physical Oceanographer.

Jeffries Wyman, Associate Professor of Biology, Harvard University; Associate in Oceanography.

John McGilvray, Jr., Comptroller.

Helen F. Phillips, Secretary to the Director.

William C. Schroeder, Business Manager.

William Schroeder, Superintendent of Buildings and Grounds.

List of Contributions

LIST OF CONTRIBUTIONS

FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

For a list of Contribution Numbers 1 to 100 see previous issues from 1933 to 1940. A separate list of these numbers may be obtained on request.

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